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The Proceedings

OF

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PART A

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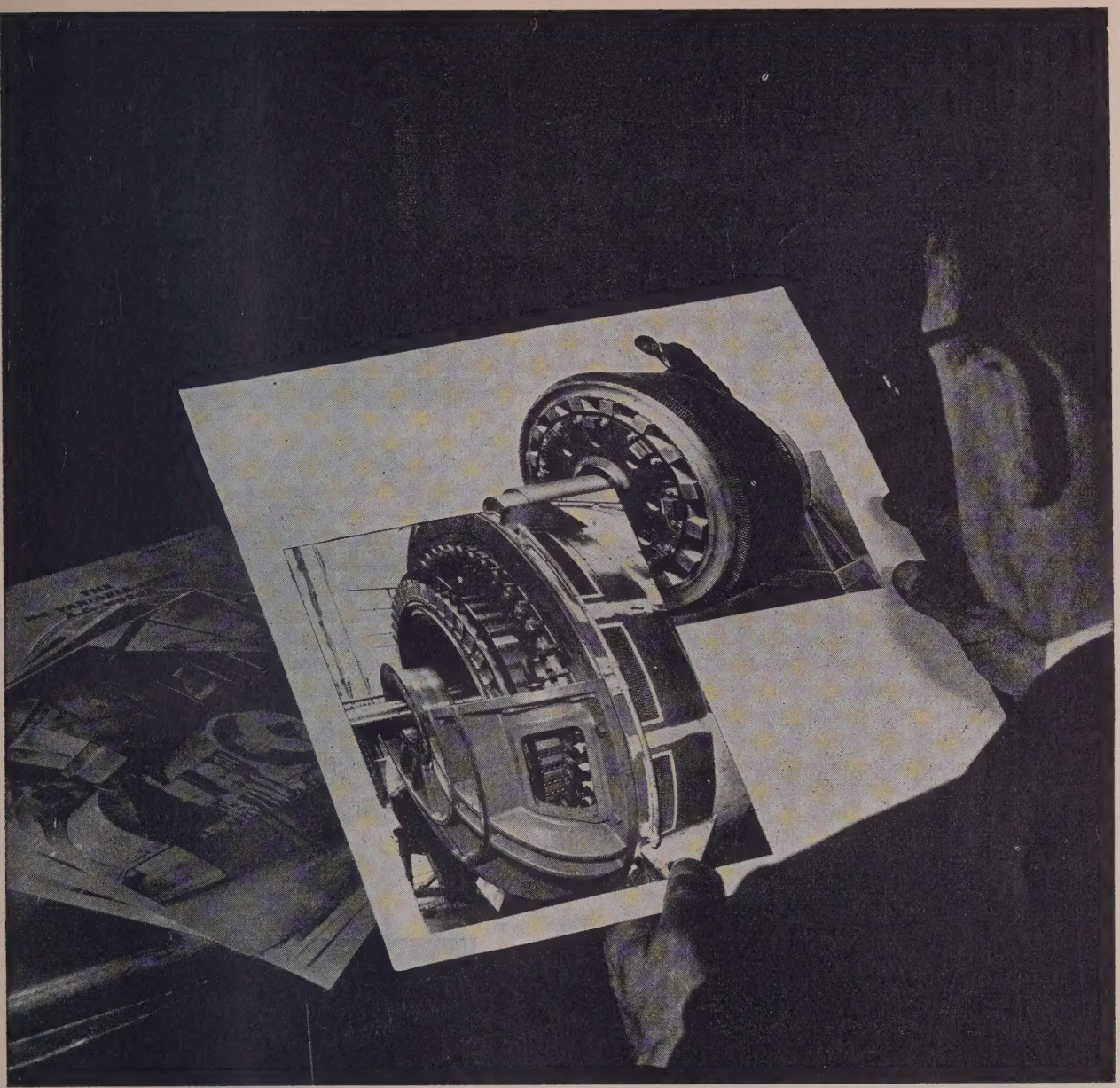
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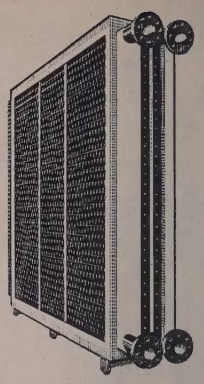
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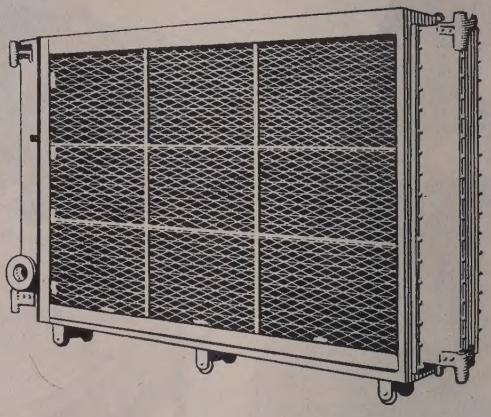
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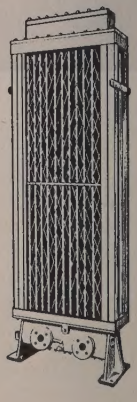
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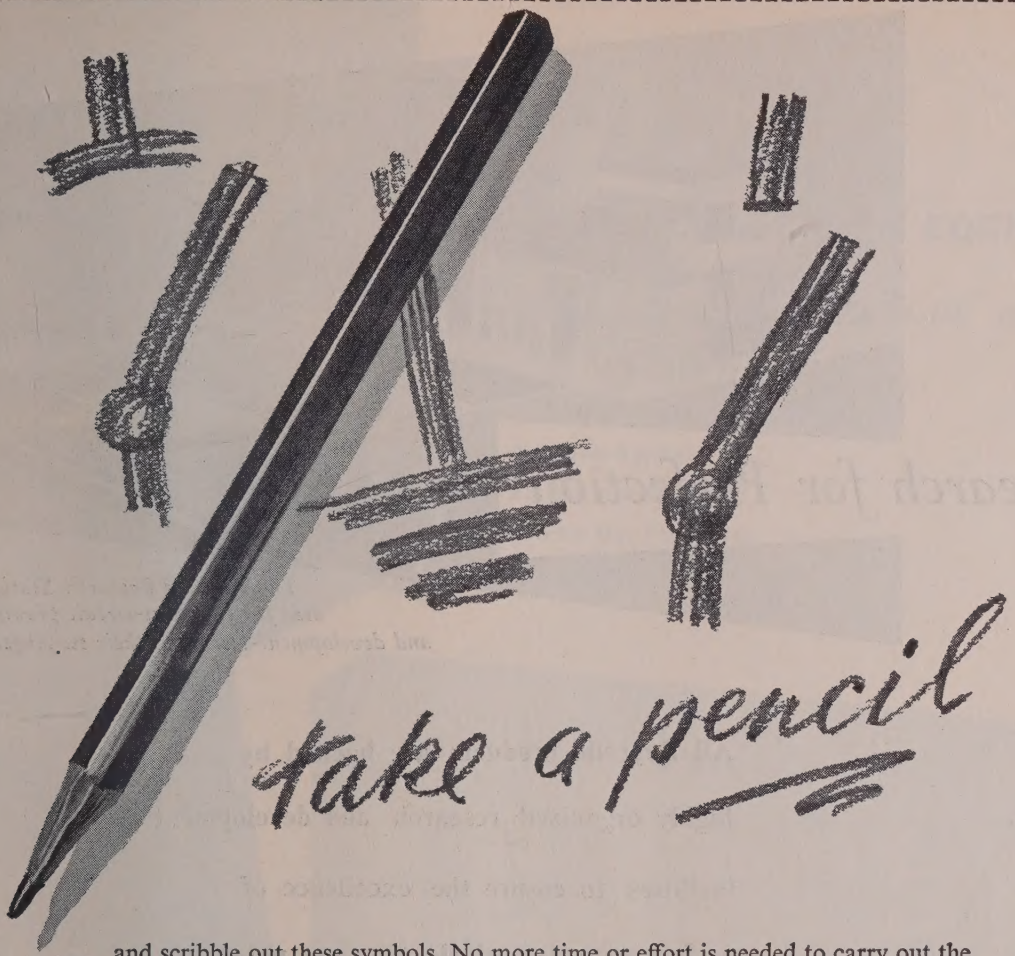
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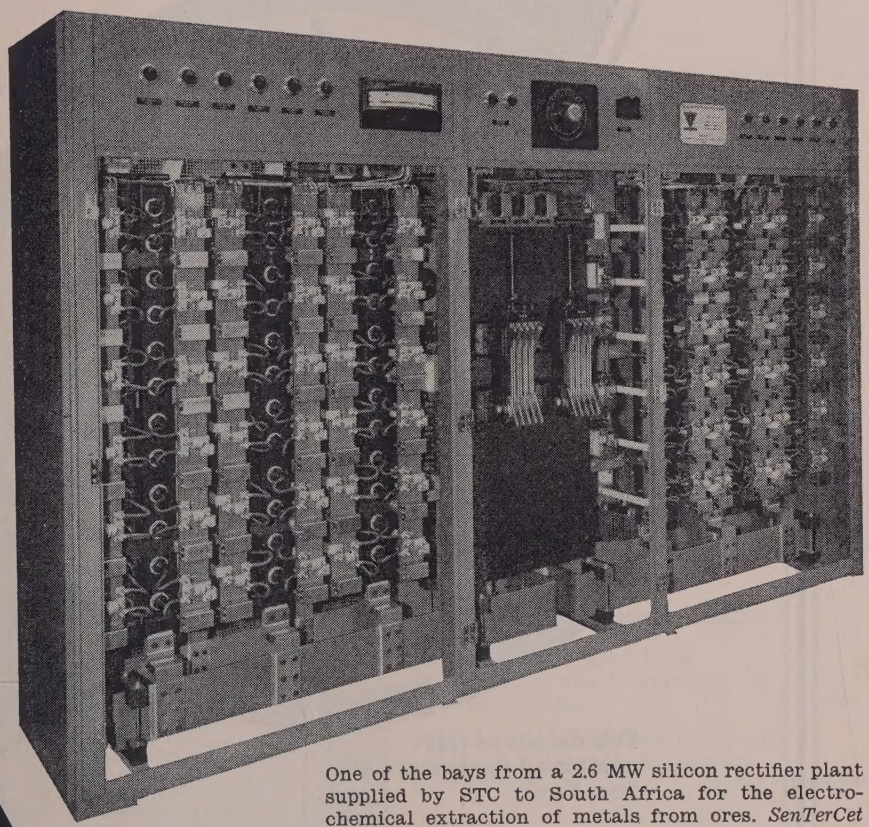
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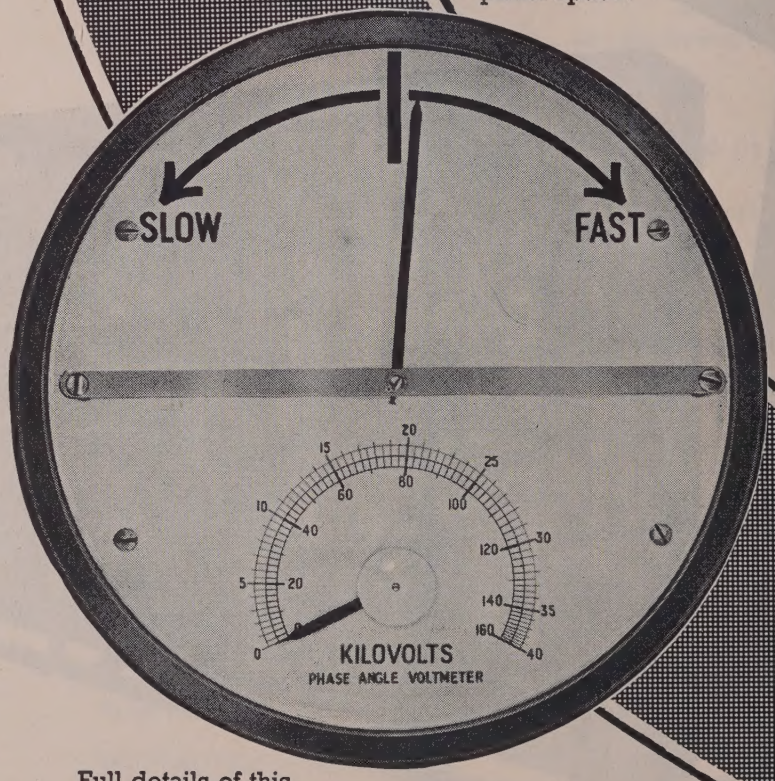
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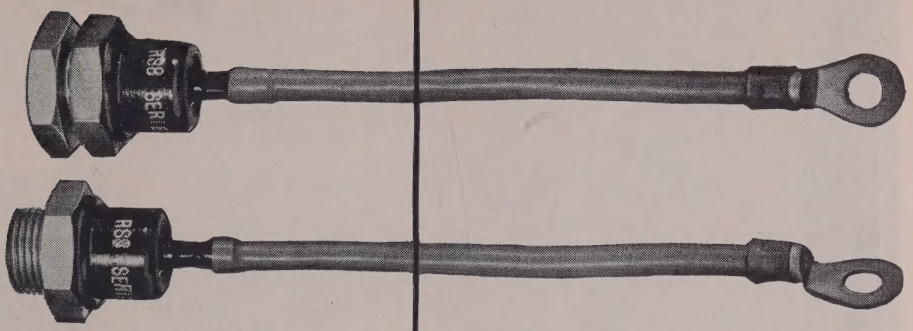


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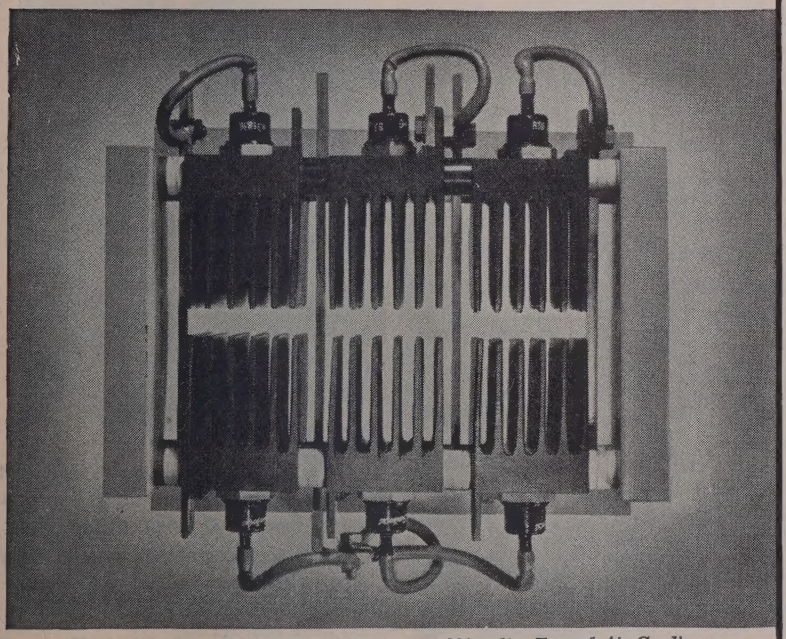
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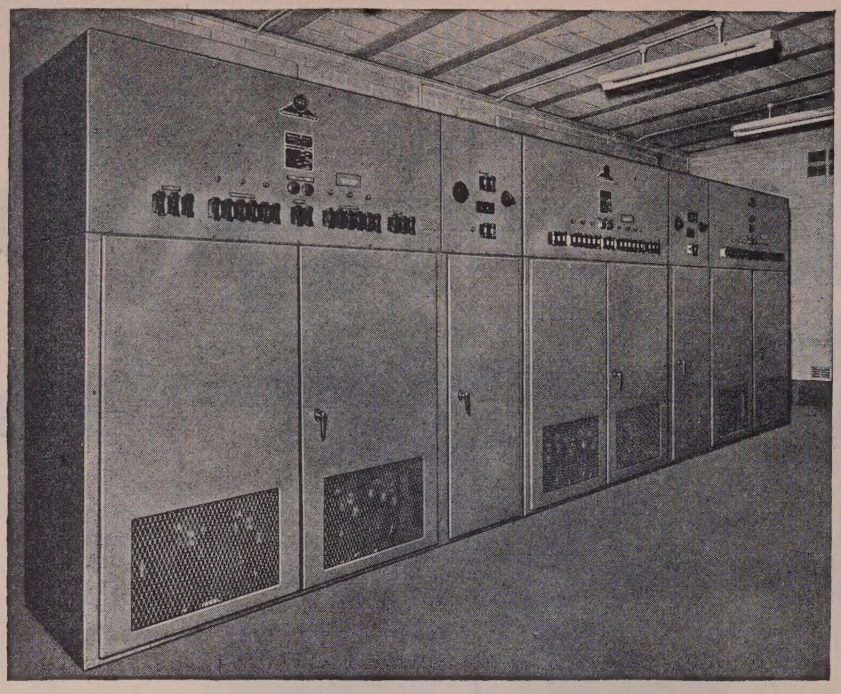
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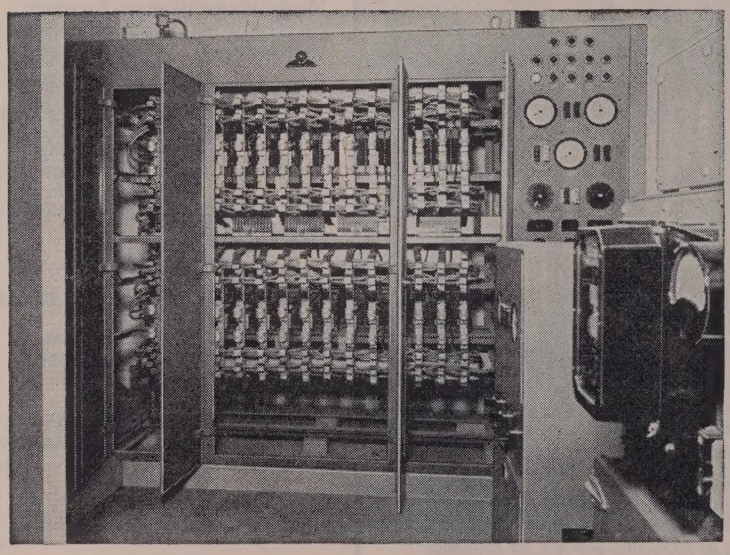
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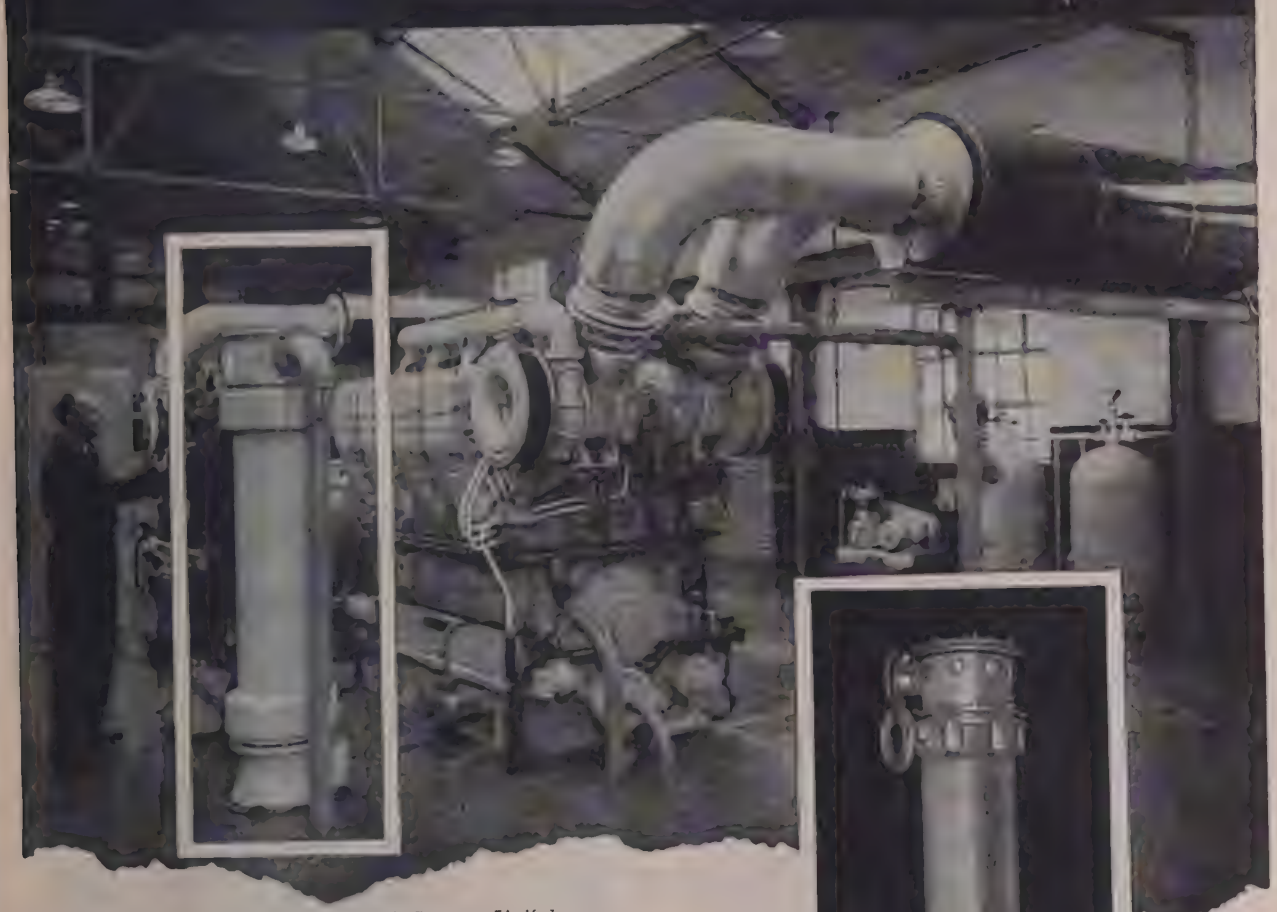
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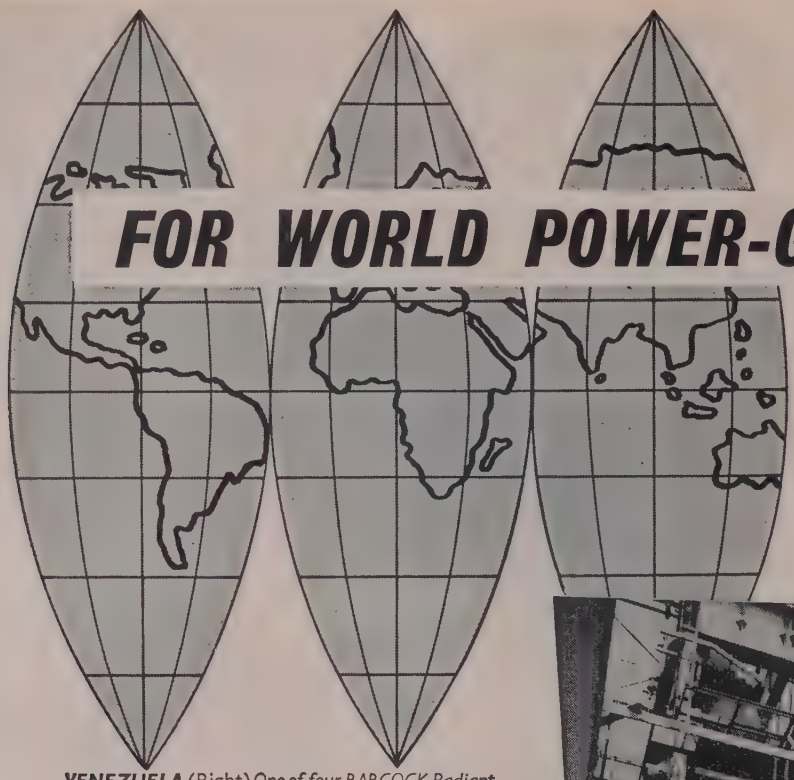
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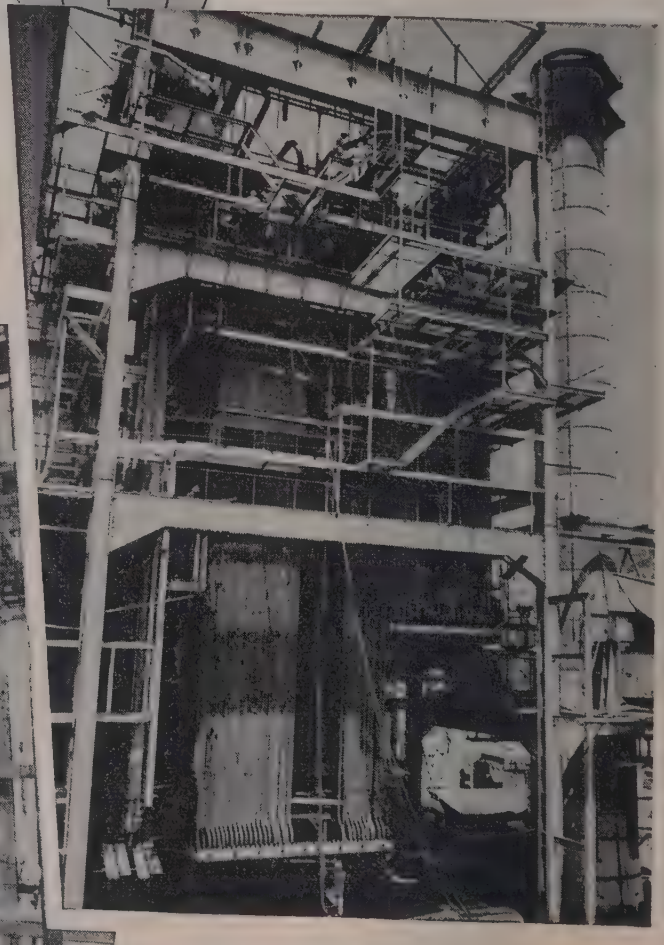
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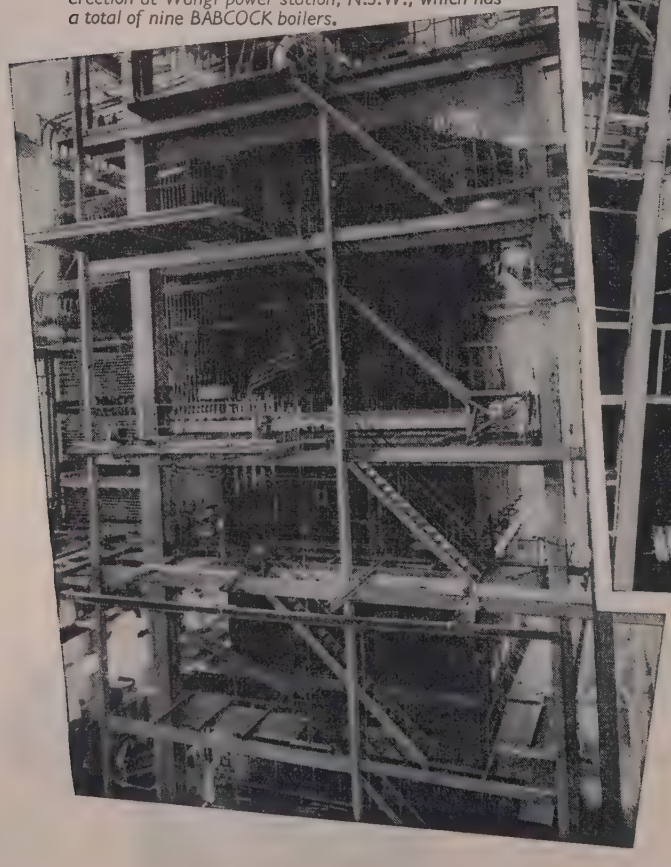
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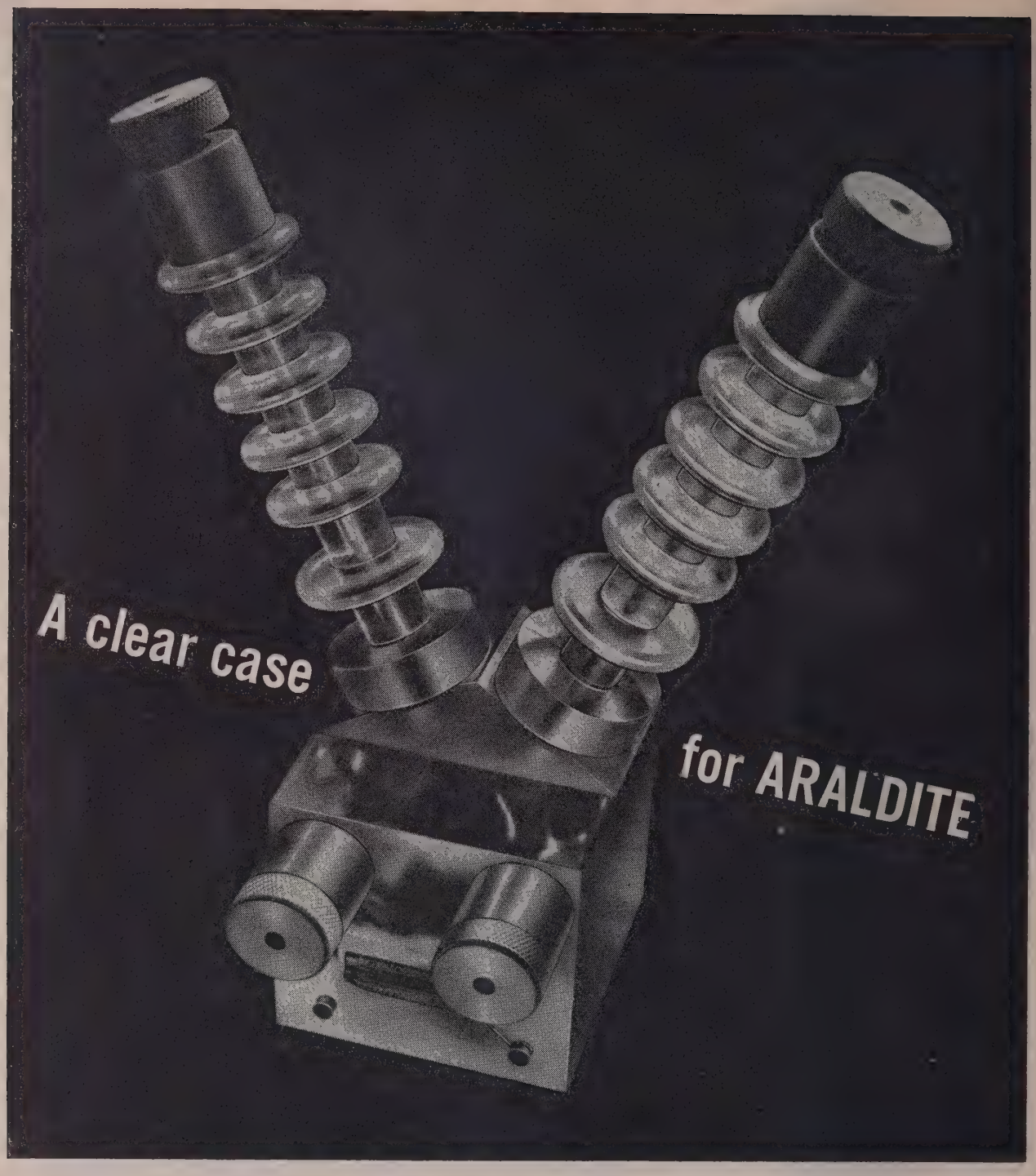


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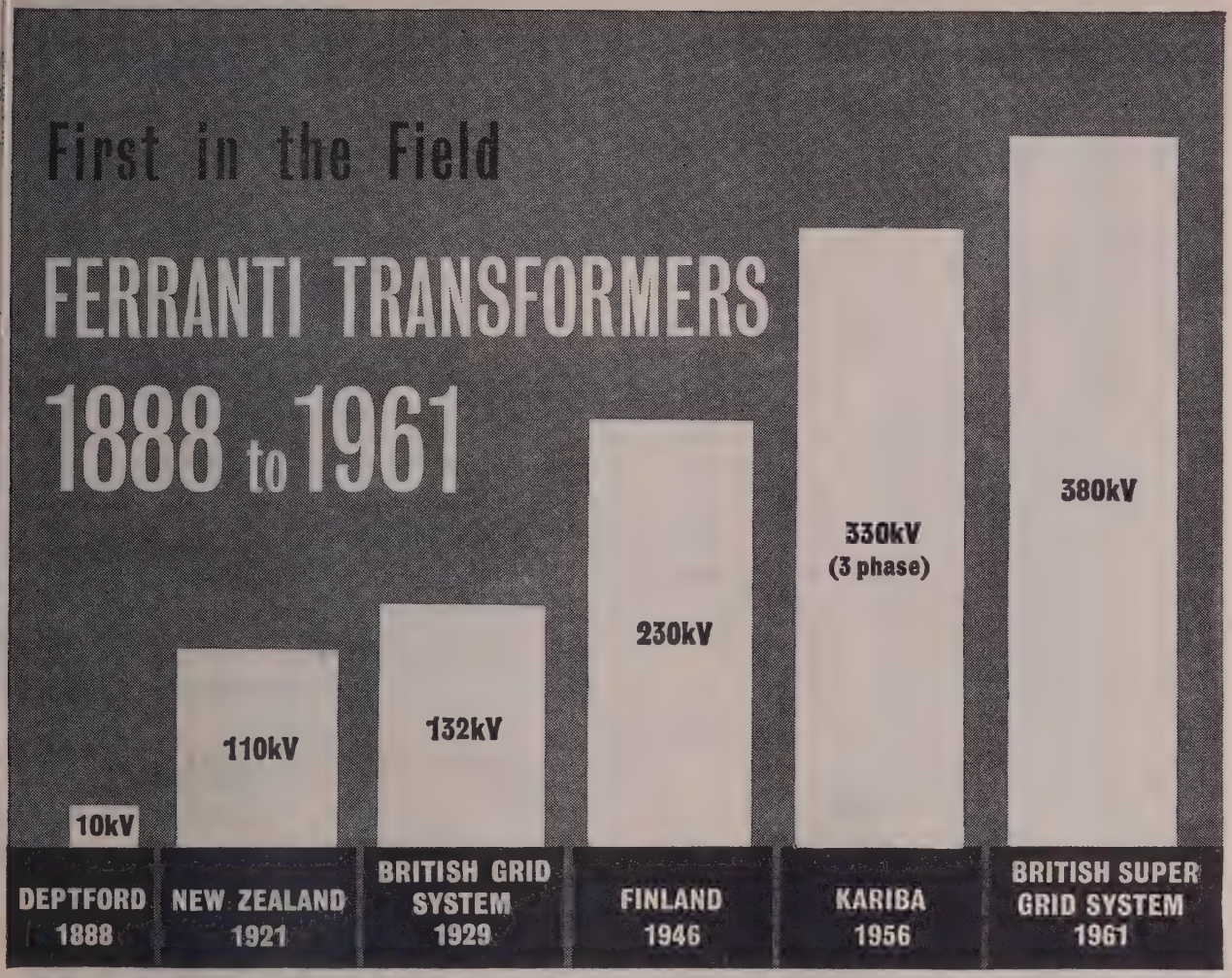
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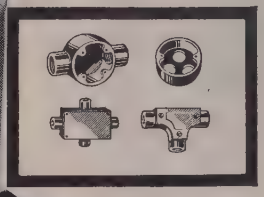
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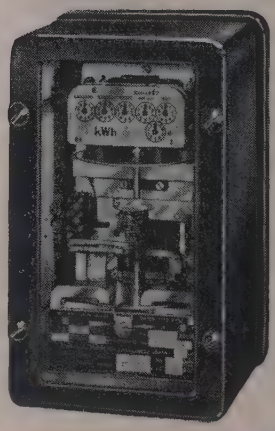
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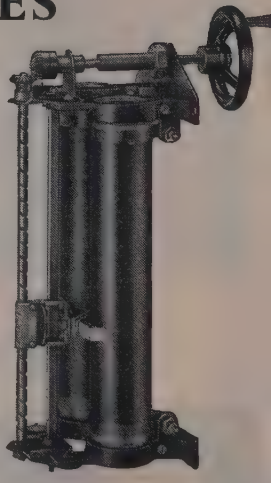
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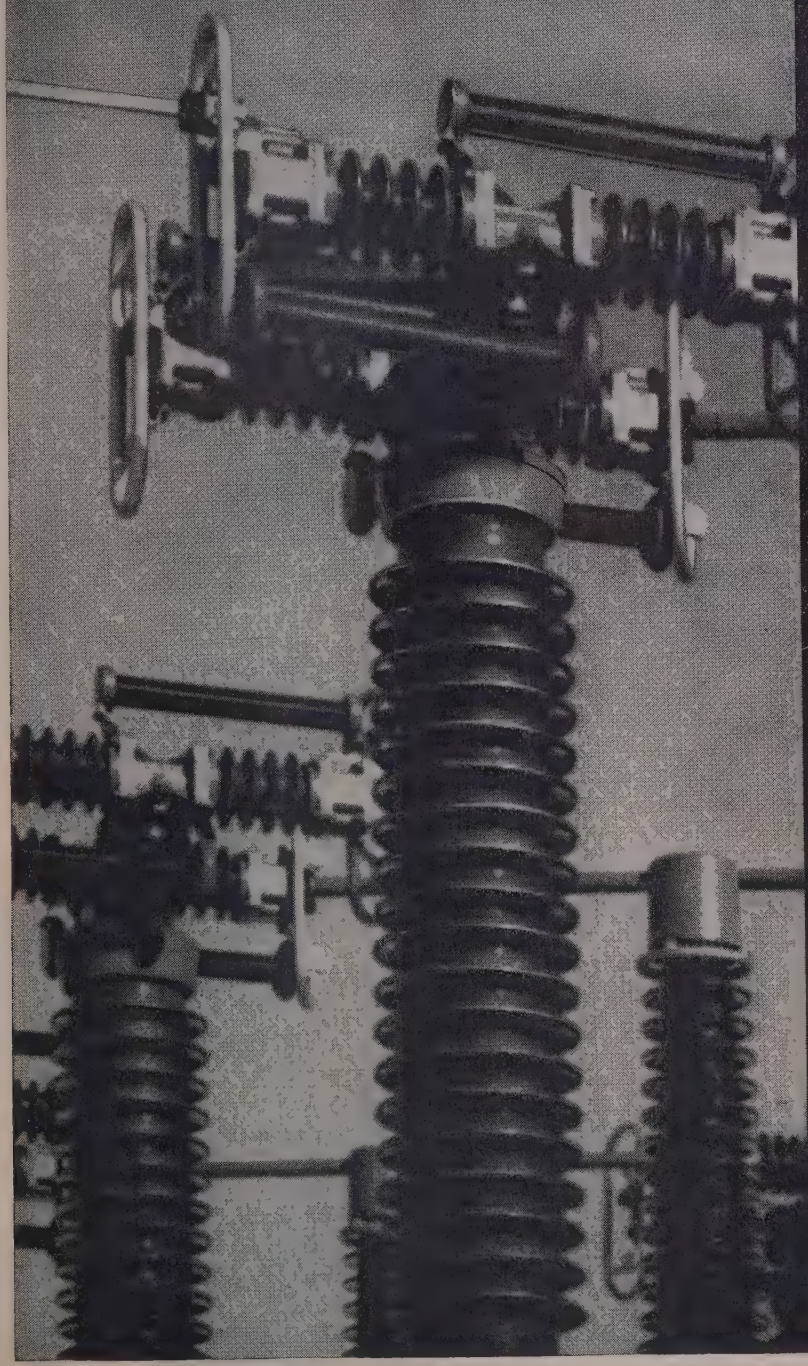
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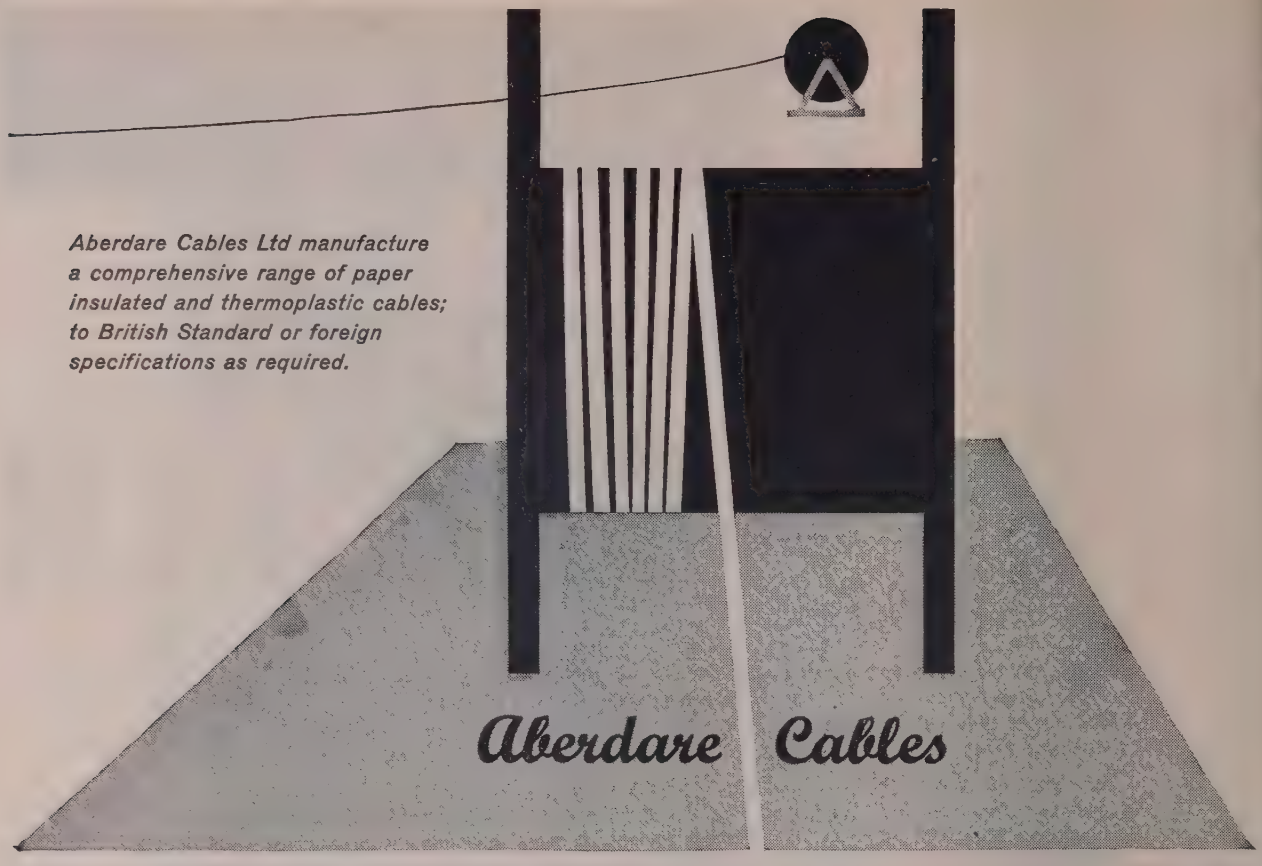
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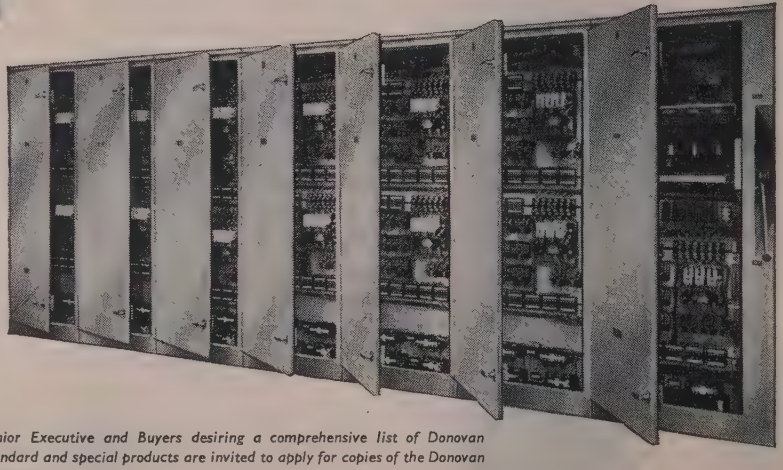
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in the picture

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Left. One of the five 11kV 250MVA switchboards.

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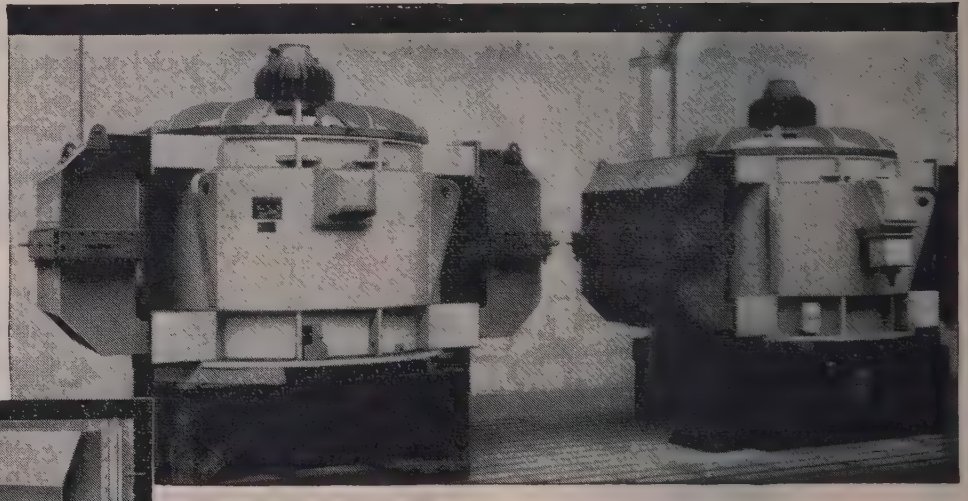
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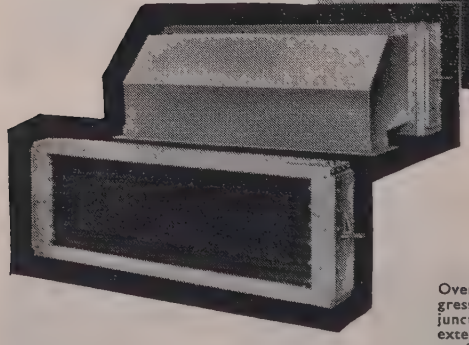
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Right: 2 (of 8) 1600 h.p. induction motors. Vertical spindle, closed air circuit type with coolers by Spiral Tube. For pump drives, Brooklyn Pumping Station, Melbourne.

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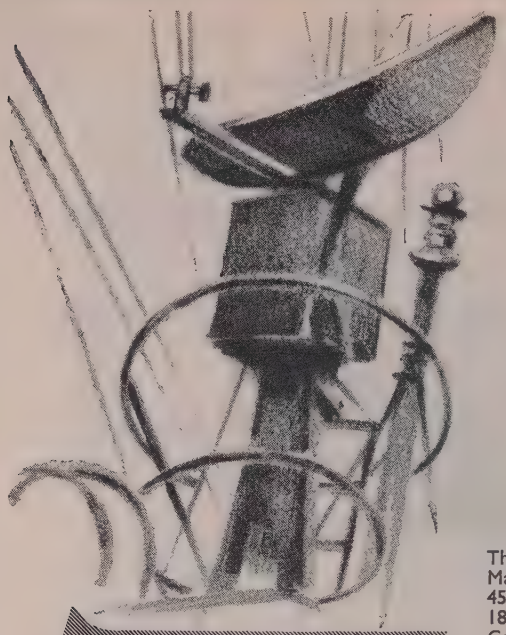
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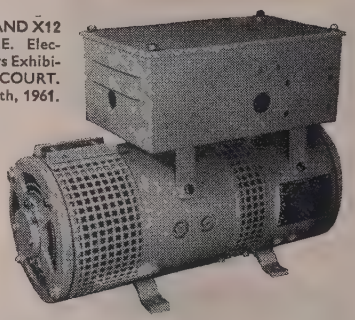
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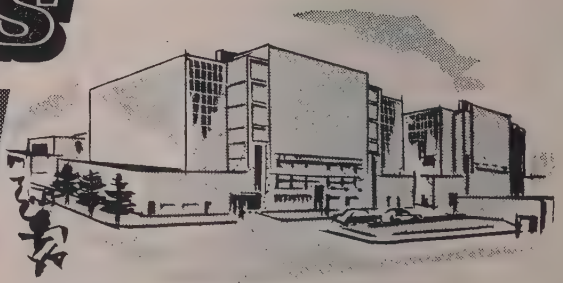
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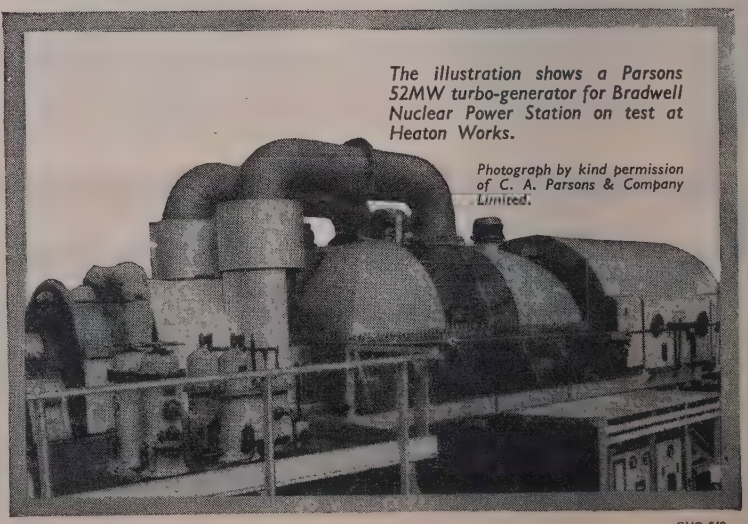
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The illustration shows a Parsons 52MW turbo-generator for Bradwell Nuclear Power Station on test at Heaton Works.

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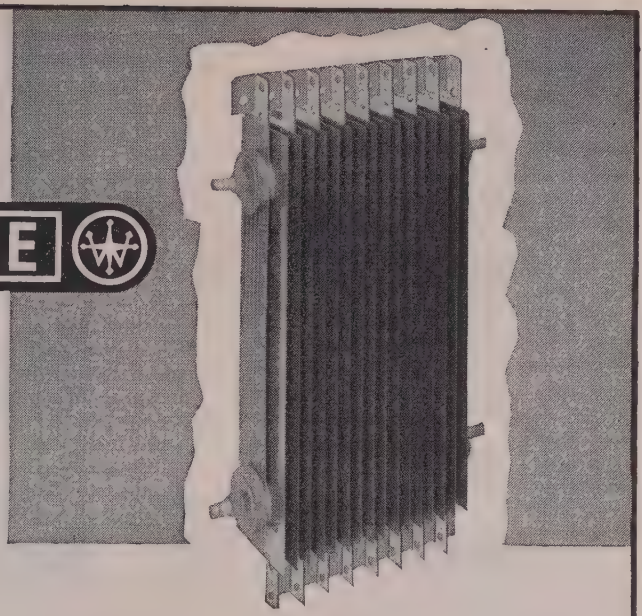
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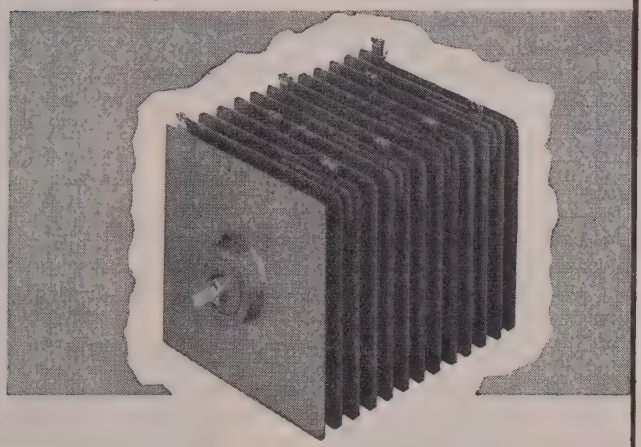
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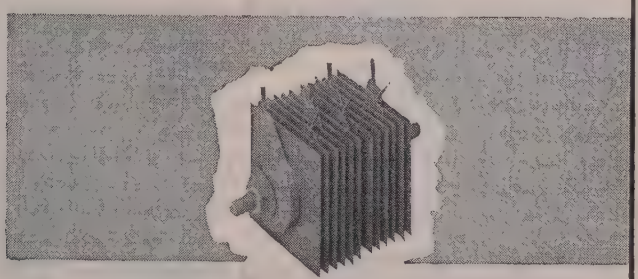
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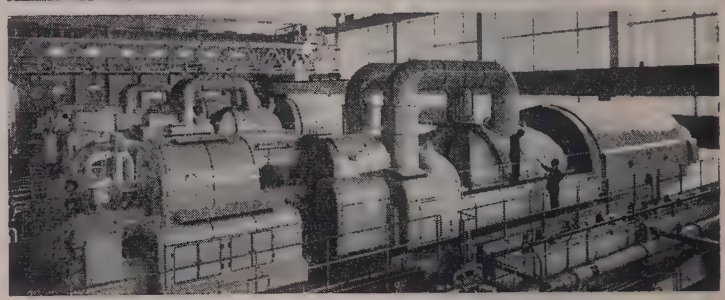
One of four PARSONS 200 MW cross-compound turbo-generators at Richard L. Hearn generating station, Canada



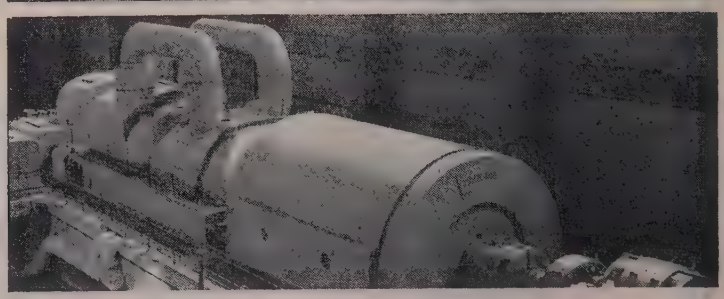
One of three PARSONS 120 MW turbo-generators at Kincardine power station, Scotland



Two PARSONS 60 MW turbo-generators at Little Barford power station, England



Three PARSONS 100 MW turbo-generators at Ferrybridge power station, England



One of four PARSONS 120 MW turbo-generators at Drakelow power station, England

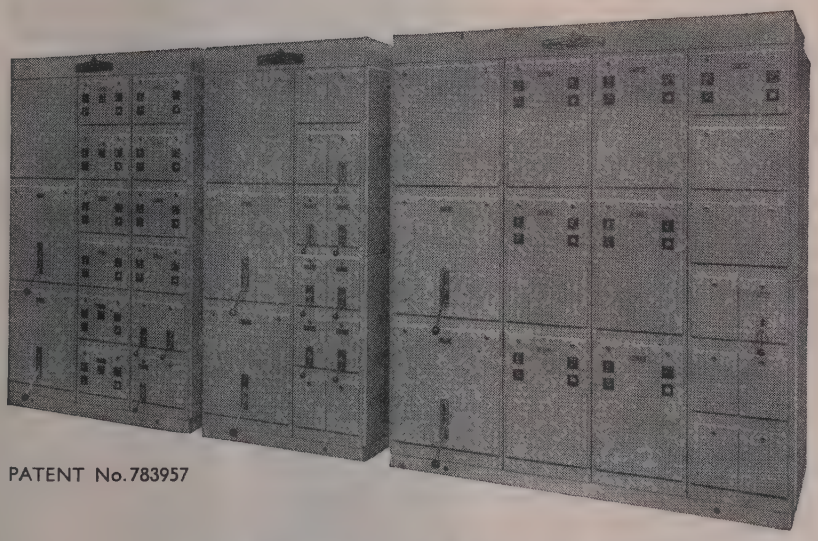
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HG1004	100	45 mA	10 mA	100 μa
HG1005	100	45 mA	5 mA	50 μa
HG1006	100	45 mA	5 mA	100 μa
HG1007	75	45 mA	20 mA	50 μa
HG1008	75	45 mA	20 mA	100 μa
HG1009	75	45 mA	10 mA	50 μa
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VOL. 108. PART A. NO. 37. FEBRUARY 1961

The Institution of Electrical Engineers
Paper No. 3355
Oct. 1960
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INAUGURAL ADDRESS

By Sir HAMISH D. MACLAREN, K.B.E., C.B., D.F.C.,* LL.D., B.Sc., President.

'A REVIEW OF ELECTRICAL ENGINEERING IN THE ROYAL NAVY'

(*Address delivered before* THE INSTITUTION *6th October*, 1960.)

It is traditional and appropriate that your incoming President should begin his Inaugural Address with an acknowledgment of the high honour which the members of The Institution have conferred on him by electing him to that most eminent and onerous of all offices which an electrical engineer can fill—President of The Institution. I am indeed deeply conscious of that honour, and equally conscious that I am not going to find it easy to maintain the high standard which my predecessors in office have set.

I am, however, tremendously encouraged, in contemplating my coming year of office, by the insight gained during my five years as a Vice-President of the service rendered to our Institution, and of the support given to the President, by all active members at Headquarters and in the Provinces, and by our Secretary and his staff. Also, as from the end of this month, I am fortunate in being spared the prospect of attempting to combine my duties as President with those of the Director of Electrical Engineering at the Admiralty. For this I am most grateful to the Board of Admiralty for having agreed to such a timely date for my retirement. I am also fortunate to have the prospect of the coming exhilarating Presidential year to soften the blow of saying goodbye to the Admiralty service in which for 34 years I have enjoyed a professional life of absorbing interest.

There must be few facets of electrical engineering which are not reflected in modern warship design, ranging from the generation and distribution of power by steam, Diesel, gas turbine and atomic fission to the very complex installations required for computation and communication for modern control systems, based on thermionic, magnetic and semiconductor techniques. The fact that the cost of the electrical installation in a present-day warship approaches 30% of the cost of the ship as a whole will perhaps help to convey to you the importance of this aspect of design and construction. Fortunately, the D.E.E. is not directly responsible for some of the more specialized applications: but he is responsible for the installation of all electrical equipment and for its compatibility in operation in the ship as a whole.

In selecting a subject for this Address from such a wide field, I found myself suffering from an embarrassment of riches; but 'security' came to my aid in eliminating many items, and in any case it seemed more appropriate to select a subject which would be of interest to the largest number of those good enough to honour me by their presence this evening.

I shall therefore, rather ambitiously, attempt to review the application of electrical engineering in the Royal Navy from the earliest days down to the present time.

1852 to 1904

Electricity seems to have been first applied to the service of the Royal Navy in 1852, when an electric telegraph was installed between Whitehall and the Commander-in-Chief, Plymouth. Up to then the 220 miles were spanned by 22 semaphore stations, and it was claimed that Whitehall could send a message and get an answer back in 15 minutes. This makes one long for the good old days! The first application of electricity afloat was in the 1870's, when electric firing of guns was introduced. Pile-type batteries were used consisting of 160 sheets of alternate copper and zinc, separated by 'fearnought'—a kind of flannel used for stokers' trousers—dipped in a mixture of vinegar, salt and water. These were later replaced by Leclanché cells, with an earth return, and this system has been retained to the present day in firing circuits. In 1875 the first dynamo was installed in a warship. This was to provide power for a searchlight for use against torpedo craft. It is probably this early association with torpedoes which led to the torpedo officer becoming responsible for all electrical apparatus afloat until 1946, when the Electrical Branch was founded. In 1876 searchlights were installed in H.M.S. *Minotaur*, using a Wilde generator, belt driven from a pumping engine. H.M.S. *Inflexible* was fitted with an electric lighting and searchlight installation in 1881.

In this ship Swan incandescent lamps were connected in series groups to an 800-volt d.c. generator, which is shown in Fig. 1. Needless to say, this was not very satisfactory, and within a year the first fatal accident is recorded, not altogether surprisingly; 80 volts was then adopted as standard, and by 1885 some 100 vessels had searchlights and 10 had electric lighting. The lamps, illustrated in Fig. 2, had carbon filaments which terminated in platinum wire loops fused into the glass bulb.

The cables were rubber insulated, with a serving of cotton tape

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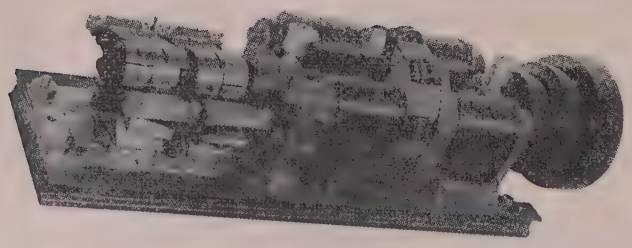


Fig. 1.—800-volt generator from H.M.S. *Inflexible*.
Overall length, 4 ft.

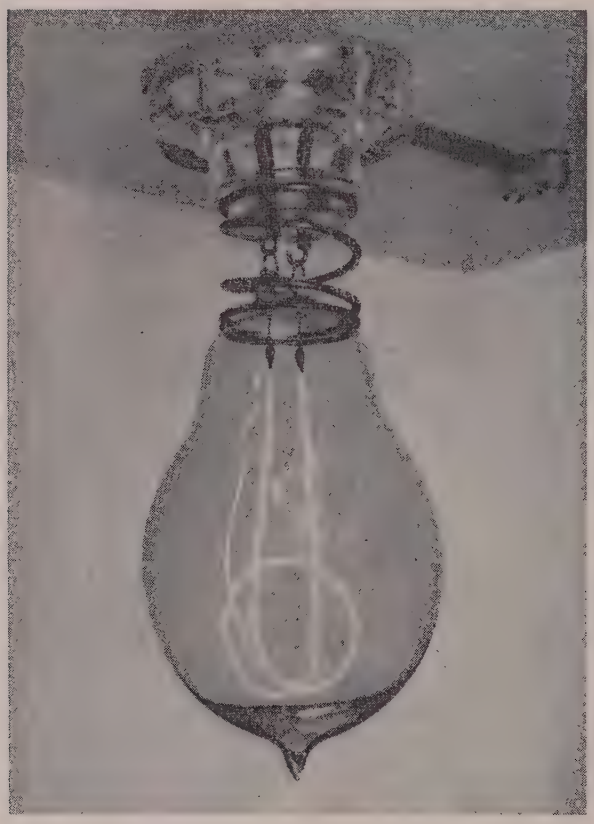


Fig. 2.—Early carbon-filament lamp.

coated with preservative. They were run in teak casings and embedded in putty. This was later replaced by a lead sheathing with layers of jute yarn as insulation instead of rubber. These all gave trouble, but a change to rubber insulation with a lead sheath in 1888 was much more successful, and this basic type of cable, with of course many improvements, continued to be used up to the end of the Second World War.

A first-class ship of 1886 was fitted with three dynamos each giving 200 amp at 80 volts. By 1900 the demand for electric power had grown to such an extent that dynamos giving 600 amp were being fitted. In 1899 the Admiralty Electrician, who had just been appointed to the Constructor Manager's Department of Portsmouth Dockyard, recommended that the voltage should be increased to 100, the voltage drop on an 80-volt system having become excessive as the electrical loading increased.

Although lighting and searchlights constituted the main loads in these early warships, the electric motor had been introduced and had proved its usefulness. By the end of the century, electric motors were used for ventilating fans, various auxiliary drives, capstans and even for training and elevating guns.

Electricity had now made a place for itself in warships, and in 1898 the Board of Admiralty decided that the torpedo officer was to be responsible at sea for electrical communication and electric motors. Soon after the Electrician had been appointed to Portsmouth Dockyard, the Board decided to have this new thing, 'electricity', thoroughly looked into, and they appointed a committee to do so. This resulted in the appointment in 1903 of Charles Wordingham—President I.E.E. in 1917 and 1918—as the first electrical engineer at Admiralty Headquarters. There was now recognition of electrical matters both at Headquarters and at sea.

In referring to this period, mention must be made of a very remarkable torpedo officer, Captain H. B. Jackson, who experimented with methods of detecting the newly discovered Hertzian waves. While serving in H.M.S. *Defiance* he developed a coherer, and in 1896 he was successful in establishing W/T communication between H.M. Ships *Defiance* and *Scourge* over a range of 5800 yd. During that year he met Marconi and the two pursued research in the friendliest manner. In 1899 Jackson's persistence resulted in the Admiralty agreeing to Marconi installing his equipment in four ships with a communication range of up to 70 miles.

1905 to 1939

By 1905 it was being proposed to raise the voltage in warships to 220. Tests at the time demonstrated to the satisfaction of the Navy that '220-volt electric shocks were unpleasant but not dangerous'. They must have been tough in the Navy in those days! This voltage then became the standard for large ships, H.M.S. *Defence*, a cruiser completed in 1908, being the first ship to be so fitted. Hitherto there had been a single central switchboard such as that shown in Fig. 3. Each generator had



Fig. 3.—Early type of switchboard.

had its own set of busbars, and service feeders had been connected to alternative busbars by various types of change-over devices. The *Defence* was also the first ship to be fitted with a ring-main system of distribution, a system which, with the many improvements born of subsequent experience in peace and war, is still at sea in many of our larger ships. The main objectives of the ring-main system as stated in the 1906 specification were 'to reduce the number of holes in vertical bulkheads and to simplify the wiring for electric power and lighting generally; also to effect a saving in the amount of cable used'. It certainly went a long way towards achieving these objectives.

The ring-main system in the *Defence* was supplied by four generators, three of 105 kW and one of 210 kW capacity. Circuit-

breakers were provided to protect each generator and at each service tapping point on the ring main. In the *Defence* the generators were grouped together, but in an improved design of ring-main system in H.M.S. *Orion*, in 1910, the four 200kW generators were installed in separate compartments.

In the early ring-main system, electrical equipment connected directly to it had to be in watertight enclosures capable of withstanding immersion in sea water to a specified depth. This was to ensure that flooding in any part of the ship involving the ring-main equipment would not lead to short-circuits and loss of all power. Hand-operated switches were provided to isolate damaged or flooded sections of the ring main, but the generators themselves, and the distribution equipment fed from the water-tight switchgear, were non-watertight.

Experience during action in the 1914–18 War revealed that the so-called watertight equipment rarely remained so in service, and that it was not easy to isolate damaged or flooded sections under the stress of action. During that war it was necessary to increase the number of isolating switches and to arrange for their operation from a more accessible deck and one which was not so susceptible to flooding. A system was also devised for automatically isolating non-watertight equipment from the ring main by means of a device called a 'main guard', shown in Fig. 4.

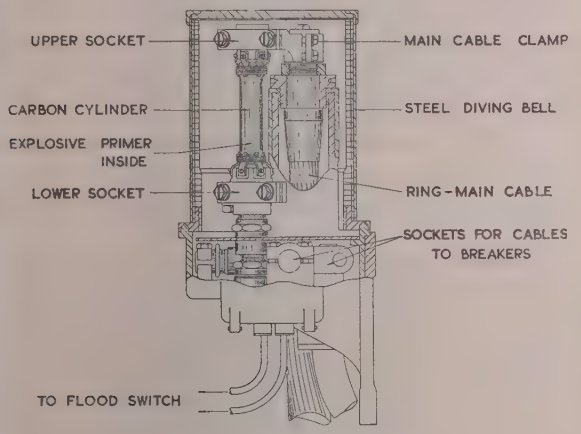


Fig. 4.—1 200 amp main guard.

This was an unusual piece of apparatus consisting of a carbon cylinder called an 'interrupter' enclosed within a miniature diving bell. The interrupter carried the full load of the generator or the group of branch breakers being supplied from the ring main. Explosive primers of the type used to initiate the firing of cordite in the ship's guns were mounted within the carbon interrupter and connected to electrodes in a flood switch, so that, when water in a compartment rose to the level of this switch, the resulting current fired the primers, shattering the carbon cylinder and thus disconnecting the item of non-watertight equipment from the ring-main before a short-circuit could occur.

The seriousness of flooding as a general problem is evidenced by the special measures adopted in H.M.S. *Hood*, which was designed in 1916 and, incidentally, continued in service till sunk by the *Bismark* in 1941. The *Hood* was fitted with eight 200kW d.c. generators, each having slip rings in addition to its commutator, so that an alternative a.c. supply of 200kVA at 135 volts 25c/s was obtainable when required from each generator to supply an a.c. ring main installed solely to provide power for submersible pumps to deal with flooded compartments.

After the 1914–18 War the Admiralty reviewed the experience to date of the generation and distribution of electrical power in warships, and in 1919 suggestions were called for from those concerned with the problem. The review included the possible introduction of alternating current.

The report issued in 1921 was strongly in favour of retaining the ring-main system in all except the smallest ships, but with certain modifications born of experience. It was also envisaged that the largest generator required in the future would be 250kW. The review justified the continuing use of direct current as having a balance of advantage compared with alternating current, having regard to the relatively restricted applications of electricity in warships at that time. Considerable importance, perhaps more than was justified, was attached to the ease with which speed control was readily available with direct current. It is interesting to note that one argument quoted against alternating current was that 'a Russian battleship, the *Volga*, had been fitted with an a.c. system which must have been a mistake because it was not repeated in later ships'.

Following this policy decision to retain direct current, effort was continued on developing the ring-main system, one notable improvement being the provision of automatic circuit-breakers, known as 'ring-main breakers', to enable sections of the ring main to be isolated. These operated on over-current and could be closed or opened from the main controlling switchboard. Another improvement was the development of the fuse-release switch to take the place of the main guard. This is toggle operated and held in the closed position against a spring by a stainless-steel fuse wire, which in turn is connected to the flood switch. The device, illustrated in Fig. 5, still survives in d.c. ships.

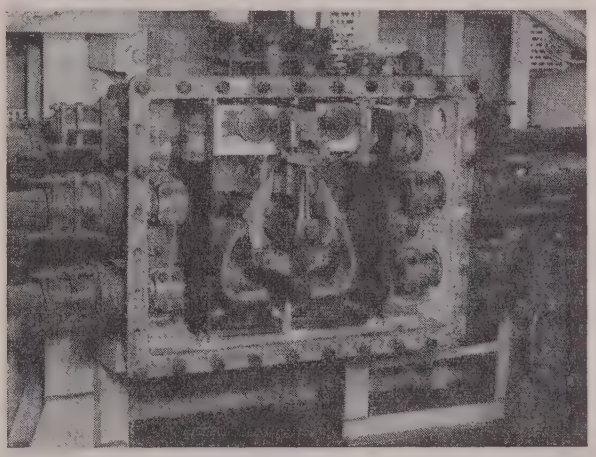


Fig. 5.—Fuse-release switch.

The possibilities of a change from direct current to alternating current were again seriously considered in 1932. It was assumed for the purpose of the investigation that a destroyer would have two 40kW turbo-generators with one standby set of 20kW, and a cruiser, four 225kW turbo-generators. These installations were still too small to justify a change to alternating current; but, had the very rapid rate of increase in demand for applications of electricity in the subsequent decade been foreseen, the decision might well have been different.

In the middle 1930's there was a considerable expansion in warship construction. New designs of cruisers and battleships were put in hand, and a new type of ship for the Royal Navy, the aircraft carrier, came into being. The first aircraft carriers were conversions from existing hulls, such as the *Furious* and the *Glorious*, but new ships designed from the outset as aircraft carriers were being constructed before 1939. These larger and

newer ships demanded more generating capacity, and the 1936 battleships, the *King George V* class, were designed with eight 300 kW generators, and the first aircraft carrier, the *Ark Royal*, had six 400 kW generators.

At this stage it was found necessary to take stock of the electrical supply position and deal with two important problems. First, there was growing doubt whether the fault protection system employed in the ring main was correct and reliable, particularly as regards its discriminating properties. It is essential that branch breakers should clear faults on feeder cables without the ring-main breakers opening, and similarly ring-main breakers should clear faults on the ring main itself without the generator supply breakers opening. Second, there was a lack of knowledge of the short-circuit current characteristics of the larger systems and of the performance of the circuit-breakers on low-impedance faults.

H.M.S. *London* was made available in late 1938 to enable an assessment of the problems to be made. The trials consisted of imposing a comprehensive series of low-impedance faults on the system with various combinations of generators running in parallel in order to determine the maximum possible short-circuit current, and to apply the most stringent discrimination tests to the circuit-breakers. The maximum short-circuit current measured during the trials was 33 000 amp with the four 300 kW generators in parallel, and this was just about the maximum which the type of ring-main switchgear then in use could interrupt safely. Discrimination between the circuit-breakers was found to be unsatisfactory, and, to correct this, new over-current relays had to be designed which could be fitted in existing ships. High-breaking-capacity fuses were also fitted as back-up protection in branch breakers, and switchgear manufacturers were given the task of developing breakers of higher breaking capacity for future installations.

The urgent problem was how to deal with the new battleships which were then being built with eight generators, which, when run in parallel, would produce a short-circuit current beyond the breaking capacity of the switchgear in use. It was decided to run the ring-main system split in these ships so that no more than four 300 kW generators would supply one side of the ring main. One of the original objectives of the ring-main system, that by running with a closed system only limited reserve generator capacity was necessary, had therefore to be sacrificed, and subsequent systems were considered as a number of sections, each carrying its own reserve generator capacity, which could be interconnected in an emergency if any generators failed.

During this period the growth of demand for power was steady but not spectacular. Early hesitation over the use of electric motors for auxiliary drives was gradually overcome in all fields except for gunnery applications. Experiments with gun-driving motors were carried out during the first decade of the century, and in 1906 two 12-in gun mountings were installed in H.M.S. *Invincible* with electric training and elevating using the Ward Leonard system. The training motors were only 25 h.p., and it is not surprising that after a short time in service the installation proved to be under-powered. Attempts at electric drive of gun turrets were abandoned until just before the 1939 War, when the metadyne system was introduced to solve the problem of remote power control. To this I shall refer later.

Not long after the very early days when crude batteries were used to provide current for firing guns, there began a steady growth in the use of electrical equipment and instruments for passing gunnery data and orders from range-finder directors to guns, and for communication generally. The increasing work involved in dealing with this side of electrical engineering was greatly accelerated during the 1914–18 War. Many of the components of fire-control systems such as plotting tables and data-transmission and communication instruments were the products of specialist firms, and this made uniformity of practice and design difficult, if not impossible. In the years between the two great wars this shortcoming was put right, and more efficient and reliable systems and their components were developed and designed in detail within the Admiralty. Much of this progress was due to the genius and leadership of Mr. H. Clausen.

One result of this effort was the installation of Admiralty-designed fire-control computers in H.M. Ships *Nelson* and *Rodney*. A standard fire-control computer and fuse-setting unit were also designed for installation in small ships. As the air menace at sea developed we thus had a background with which to tackle the new and more intricate problems of designing fire-control systems and predictors for high-angle anti-aircraft guns.

Many electrical systems and devices were designed and used for improving the control of armament, and it is difficult to single out any one for special mention. One innovation of interest was Henderson's gun-director system, which was introduced towards the end of the 1914–18 War. This made use of a gyroscope to ensure that the guns fired only when the ship was in a horizontal position when rolling. This was done by stabilizing the firing contacts and was a prelude to the day when directors and gun mountings would themselves be stabilized, thus permitting a very much higher rate of fire, independent of the movement of the ship.

Much work of far-reaching importance was also undertaken during the period under review at the Admiralty Research Laboratory. Three items are of particular interest:

(i) The plotting table, which automatically records the position of a ship on a chart.
(ii) The magslip for data transmission and reception.
(iii) An electrically-controlled oil-operated remote power system for searchlights.

The magslip is a precision selsyn type of data-transmission unit and was capable of very much greater accuracy than any other instrument available at that time and for many years later. It is now being superseded by the synchro. Detailed manufacturing drawings were prepared by the Admiralty, thus enabling production to be put in hand with a minimum of delay to meet expanding requirements in war-time. It was adopted by the Army and R.A.F., and production during the war was at a rate of many thousands per week. It set a new standard of reliability and accuracy in the transmission of signals in gunnery systems, and was later to be of particular value in providing the initiating and controlling signal for the remote power control of weapon systems to which reference will be made later.

The hydraulic control unit was adopted for the servo control in naval gunnery systems and by the Army for remote power control from the predictor of Bofors anti-aircraft guns.

1939 to 1945

In planning for war it was expected that the immediate emphasis would be on production of ships and of electrical equipment for new construction, refits and repairs. It was also expected that large-scale air attacks on London would disrupt the work of the highly experienced design staff working at the Admiralty. Plans were accordingly made for the immediate dispersal of the design teams to assist on production. This was done, but hardly had they arrived at their destinations when they were recalled to Headquarters, which had in the meantime been moved from London, as it very quickly became apparent that extensive effort would have to be devoted forthwith to research, development and design to meet and overcome the enemy's novel and ingenious devices in the war at sea.

The enemy began laying magnetic mines during the first week of the war, and ships were lost and damaged whilst counter-measures to protect ships and destroy these mines were being perfected and the necessary equipment produced. Although sweeps of a sort were produced at once, really effective sweeps could not be evolved until the characteristics of the German mine were revealed after a live mine was recovered and examined in November, 1939.

The towed skid and the magnet ship were the two most successful of the early sweeping devices. The skid consisted of a raft on which was mounted a coil energized from a wooden towing vessel at a safe distance from the skid. The magnet ship, or 'Borde', as this type of vessel was called after the first ship to be so equipped, had an electromagnet built into its bow. The magnet was 100 ft long, weighed 500 tons, and was supplied from a d.c. generator. Later the supply was changed to low-frequency alternating current so that the sweep could deal with mines of north or south polarity. The use of these ships had to be discontinued when the mines came to be armed with a device requiring an unknown number of actuations before exploding. Real success came when the towed buoyant-cable sweep was developed. The method consists in producing a large magnetic field in the sea by pulsing currents of several thousand amperes through a loop of buoyant cable towed by the minesweeper. It is still the standard method of sweeping magnetic mines.

Two types of buoyant cable were designed literally overnight by two firms whose names are (or used to be!) household words in the cable industry, and in each case the inventor was a Past-President of this Institution. So successful were these designs that, with relatively minor improvements, they continued to be used until the end of the war.

In addition to the problem of sweeping magnetic mines there was also that of making all ships safe by fitting degaussing coils. To meet the immediate and urgent requirements at the beginning of the war these coils were of a temporary nature and consisted of turns of cable sewn up in canvas and clipped outside the hull. Current was obtained from the ship's main electrical supply and adjusted to give the correct magnetic effect by resistance control.

The first permanent solution used a single-turn coil of rubber-insulated heavy copper strip fitted to the external plating of the hull. This, however, proved to be very vulnerable to damage even in moderate seas. After considerable research in 1940 it was decided that the degaussing cable could be effective when fitted inside the hull in spite of the magnetic screening which it had been feared would be excessive. This improvement, using conventional cable, made it possible to work at a higher voltage, and the modern system, using multicore cables with the conductors connected in series and supplied from the ship's main electrical supply, came into use with automatic adjustment of current with change of the ship's course and latitude.

Right up to the end of the war there was no relaxation in the mine and mine counter-measure contest. The enemy developed more sensitive magnetic mines with anti-sweeping devices, and later an acoustic and a pressure mine. These were the most difficult mines to sweep and destroy.

One of the first warships to suffer from a magnetic mine explosion was H.M.S. *Belfast*, in October, 1939. The hull structure was severely damaged as a direct result of the explosion, but apart from this the extensive damage to the electrical equipment from shock effect was sufficient to immobilize the ship. The first reaction was one of dismay that so many items were incapable of withstanding the shock effect of an underwater non-contact explosion. It was clear that the mechanical shock experienced in a ship as a result of such an explosion was far more severe than had been anticipated. Immediate action was taken to correct these deficiencies in design.

Designing electrical equipment to withstand shock was not new. It had been the practice for many years to do so, and to test prototype equipment on a shock-testing machine; but the impact allowed for was based upon the shock resulting from gunfire and the detonation of other weapons *in* the ship. Before this testing machine was designed, indeed as far back as 1913, important items of electrical equipment, such as circuit-breakers, had been tested for shock by mounting on a 5-in armour plate and firing a projectile at the plate from a 6-in gun at a range of 1 900 yd.

However, the shock accelerations and displacements experienced as a result of non-contact underwater explosions were of a much higher order, and work was put in hand immediately to design a new shock-testing machine to the new criteria. Fortunately, the *Belfast* provided valuable data because it was possible to pick out certain identical items of equipment, dispersed through the ship, some of which had suffered damage and others not. Tests producing corresponding damage enabled the magnitude of the shock to be established empirically. We were then able to modify and improve the electrical equipment itself or arrange to erect it on suitable shock-proof mountings. Very extensive use was made of a new testing machine which was designed and manufactured at the Admiralty Engineering Laboratory and is shown in Fig. 6. Later, similar machines were

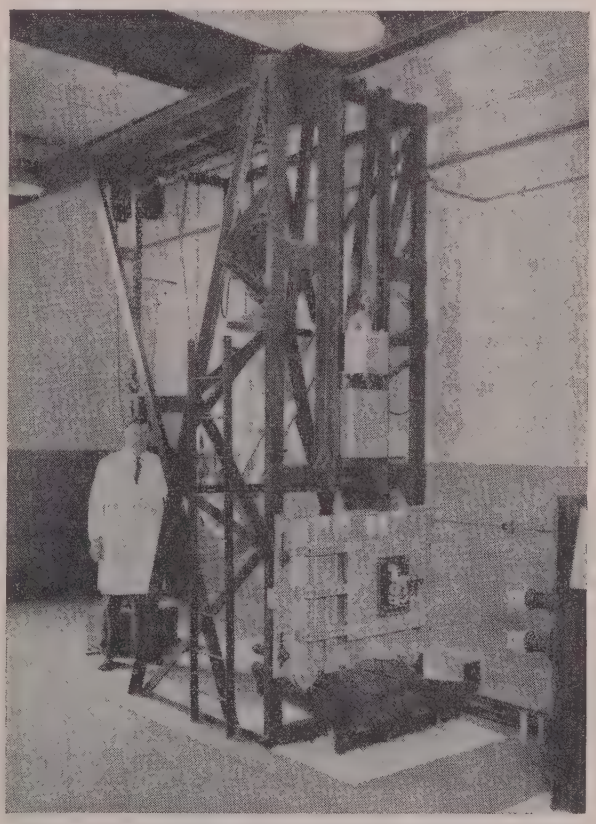


Fig. 6.—Standard mechanical-shock machine.

installed in the works of main manufacturers, and drawings were passed to the United States Navy so that they might benefit from our experience.

The evaluation of shock in ships is now an important and continuing part of the work of the Ship Department, and shock assessments are made in new classes of ships by fully instru-

menting the ships and subjecting them to underwater explosions of known intensity.

It was a great blow when H.M.S. *Ark Royal* was sunk in November, 1941. Although hit by one torpedo only, the result of the explosion was disastrous because it resulted in the immediate flooding of a boiler room and the main switchboard room. The flooding of the main switchboard, which was the control centre for the ring main and all outgoing services therefrom, was the vital factor, because, although steam was maintained for some time in the undamaged boiler room, it was impossible to close the circuit-breakers by remote control from the main switchboard to restore services. Hand operation of the breakers was impossible because of the state of the ship.

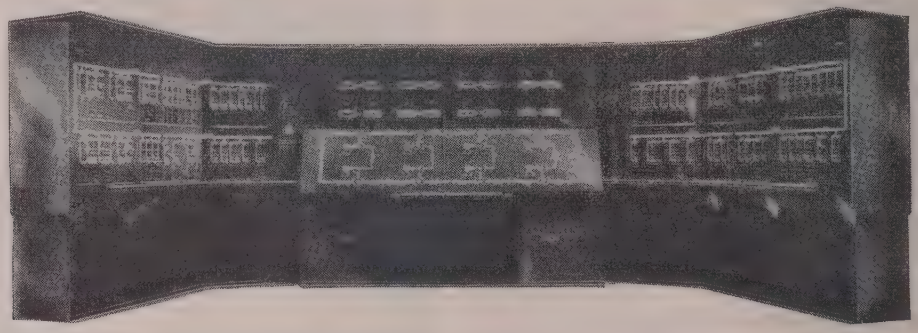


Fig. 7.—Latest type of control switchboard for d.c. ring main.

This situation had arisen because the control of the breakers from the main switchboard was based on a system in which the control wiring was always energized, and flooding or short-circuiting of this wiring could therefore change the state of a breaker by simulating the operation of either an 'on' or an 'off' push.

It therefore became of paramount importance to develop a new system. The outcome was a relay system in which the energizing power to operate or maintain the breakers in their open or closed state was contained within the breaker enclosure. Any change of state was achieved by energizing the control coil of a relay, which otherwise was dead, and which received its supplies from an independent low-voltage source at the controlling position, and in emergency from a secondary battery. The new system also made it practicable to introduce secondary control positions for sections of the ring main distributed throughout the ship, which could be brought into operation immediately if the main controlling position became unserviceable. Fig. 7 shows a typical main switchboard which contains these features, and Fig. 8 shows one of the four secondary control switchboards.

The loss of the *Ark Royal* emphasized another very important factor in the electrical supply for warships, namely the necessity for having generators capable of maintaining essential supplies after loss of steam.

The fact that the steam turbine was the most reliable prime mover was the main reason for a Board decision in 1938 to fit steam-driven generators only in future ships. The experience in the *Ark Royal*, however, demonstrated the need for alternative prime movers, and a programme of installing Diesel-generators in those ships where none existed was immediately put in hand.

The extent to which reserve electrical power should be provided in a warship had been the subject of much debate over a number of years, but it had now become clear that sufficient reserve must be available, over and above that required to meet the normal action load, to maintain essential and important action and salvage services in the event of damage. Automatic change-over switches to switch on alternative power supplies were introduced for close-range anti-aircraft gun mountings to ensure the minimum interruption of electrical supplies, and hence of gunfire, in a damaged ship whilst under attack, and their use was soon extended to other important services. The largest of these switches was able to transfer automatically a load of 110 kW in a quarter of a second on failure of normal supply. The use of these automatic switches, and indeed the hand-operated change-over switches which were also used, demanded that reserve electrical power should be available to meet the resulting transferred loads. Here again was justification for standby Diesel-generator capacity to ensure that a warship could maintain essential services, including maximum gunfire power, even though steam were lost. Throughout the war and the immediate post-war period, additional generators, both steam and Diesel, were installed in serving ships to keep pace with the increase in power demand and to ensure adequate reserve.

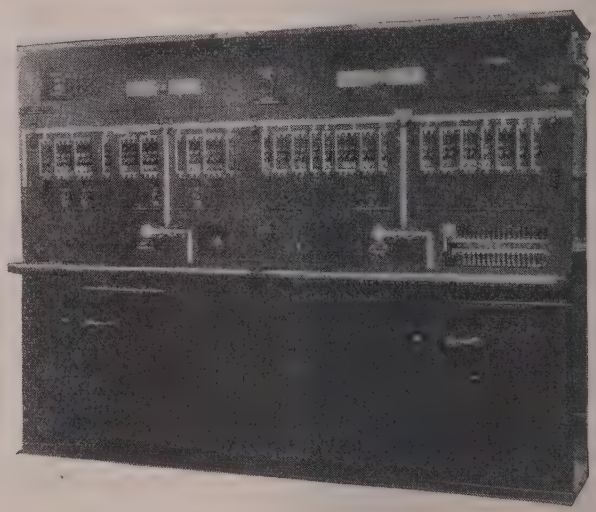


Fig. 8.—Secondary control switchboard.

The part played by electrical engineering at sea during the war was much greater than earlier experience had led us to expect. The development of remote power control systems for automatic control of armament in the early months of the war is a good example, electrical systems for this purpose having lain dormant since 1906. The objective was to eliminate the inaccuracies and time lag inevitable in existing systems in which processed data were made available to the gunlayers by magslip pointers giving angles of elevation and training. It was then

he task of the operators so to operate the gun if manhandled, r in the case of heavier gun mountings the hydraulic local ontrol, that magslip pointers indicating elevation and training ere kept in alignment with the data-transmitting pointers. Such system was acceptable for surface gunnery but was quite nadequate for dealing with rapidly moving aircraft targets. Vork was put in hand in 1939 to adapt the metadyne system hen in use for traction to the direct control of gun mountings. The first application was to multi-barrelled pom-pom mountings or close-range anti-aircraft defence. The system was based on nagslip transmission and was progressively applied, following ts success with the pom-pom mounting, to various calibres of gun mountings up to and including 6 in, and also to the director owers which control the guns. Briefly, a magslip data system produces an alternating-voltage signal which is proportional to he misalignment between the transmitter on the gun director nd the receiver on the gun mounting. This signal is fed into n amplifier where it is rectified in such a manner that the olarity of the resulting d.c. signal depends on the direction of misalignment, phase-advanced to provide stability, and finally mplified, and applied to the field of the metadyne generator as a current signal. The metadyne gives further power amplifica- ion, and the resulting output is applied to the armature of the eparately-excited constant-field gun-driving motor. Training nd elevation are, of course, treated separately.

The 'brains' of the metadyne system, namely the amplifier, processing error-in-alignment signals, was later successfully adopted to control the valves of hydraulic-powered mountings. Keen competition was maintained between the metadyne and its hydraulic rival and both are in use to-day.

When radar was introduced for range finding it was an obvious ideal to apply automatic following of the radar aerial to the metadyne-controlled director, which then became a radar aerial carrier. So the radar aerial, the gun director, and hence the gun, automatically follow the target. Later the radar was designed so that it provided its own misalignment signal and the aerial automatically 'locked on' to the target. Thus fully automatic following of the target by the gun mounting was achieved and all the necessary additional information for accurate gunnery was fed into the control systems from the stabilizer and the fire-control computer.

In the foregoing, reference has been made specifically to the metadyne as the cross-field generator used by the Royal Navy. The metadyne's twin brother, the amplidyne, is also in use for various applications and in particular for radar aerial positioning.

These developments inevitably led to an increased demand for electrical power because the requirements of stabilization and remote power control led to higher speeds and greater accelera- tions in following fast targets, while at the same time the number of close-range anti-aircraft guns in ships increased to meet the ever-growing menace of air attack.

The control of a warship under action conditions, in particular after damage, calls for, and indeed the safety of the ship may depend on, an efficient damage control organization. The organization now in force in the Navy was evolved, and proved its worth, during the war. Of course such an organization extends far beyond the control of electrical power. It includes the mechanical and hull departments of the ship as well, but its effectiveness depends upon good and reliable internal communi- cation, so here again the electrical engineer is primarily involved.

The absence of reliable secondary lighting in the early days of the war was responsible for the loss of many lives. Oil emergency lanterns proved completely useless under damage conditions and were replaced by battery-supplied lanterns, con- trolled by a hold-off relay energized by the ship's main supply, which come into operation automatically. When the *Ark Royal* was sunk she had 35 of these automatic lanterns, the most that could be made available at that time. The present *Ark Royal* has 800 lanterns carefully sited throughout the ship to ensure that every passageway and compartment is sufficiently illuminated for safety should the main supply fail.

Another war-time innovation was the action information organization requiring an action information centre. This com- partment has become the most concentrated part of the electrical installation in a warship. It is the focal point for radar and asdic information, external and internal communication, aircraft and weapon direction, and navigation. Furthermore, the growth of the radio installation, as distinct from radar, was phenomenal, and an increase in the number of transmitting and receiving channels, together with remote operation of radio- communication equipment situated in various parts of a ship, brought in its train still further increases in power demands and in the number of cables for these systems.

The increasing dependence on data systems, and on the control of electric power generally, emphasized the need for careful installation in a warship to ensure the maximum possible pro- tection against action damage. The warship had now become entirely dependent for its seagoing and fighting efficiency upon its electrical installation, and in recognition of this fact every effort was and is made to site cables to take advantage of the greatest possible protection and to duplicate supplies by alter- native routes.

It was anticipated that a large amount of damage sustained by our ships in the event of war would be by aircraft bombs, but the pattern of damage from bomb attack proved to be some- what of a surprise. The electrical layout had hitherto been based on knowledge of the effect of shell bursts, and alternative supplies from opposite sides of the ring-main system in a ship of reasonable beam had been regarded as adequate. War experience, however, revealed that the splinter pattern following a bomb explosion differed from that following a shell explosion, being no longer almost entirely directed forward owing to the velocity and trajectory of the shell when it penetrates a ship. Electrical fittings and cables on the side of the ship presented to attack usually enjoy a reasonable degree of immunity from damage by shell splinters; so that, if important cables are arranged as separate and distinct systems on each side of the ship, one system has a reasonable chance of survival. Bombs which penetrate a ship have a relatively lower residual velocity when they burst, and this results in a substantially horizontal belt of splinters which, on the deck level at which the bomb bursts, may do damage right across the ship unless the beam is very large. The circuit-breaker rooms on opposite sides of the ship had therefore to be staggered in order to provide a degree of longitudinal separation of sources of alternative power in addition to separation athwartship, and some vertical separation of alternative runs of important cables was also found to be necessary.

This new pattern of splinter damage, together with the experience of flooding and extensive areas of damage resulting from underwater torpedo explosions, raised considerable doubts as to the value of the ring-main system in warships. These factors were kept very much in mind when the change to an a.c. system after the war provided an opportunity for a new approach to the supply and distribution problem.

Nevertheless, tribute must be paid to the ring-main system which was introduced 50 years ago, and which is still in existence in some of our larger ships. Its great merit was economy in cables and bulkhead glands, because distribution was in general vertical from the ring main and conformed with the watertight subdivisions of the ship.

Many other lessons were learned as the war progressed, and

improvements were continually being made to the electrical systems and equipment throughout the whole course of the war at sea. Many years have passed since then, and during the years of peace it has been necessary to exercise unceasing vigilance to ensure that the lessons learned in those days are not forgotten, as well as to look into the future to try to anticipate problems which may arise in the ever-changing pattern of war at sea. Many aspects of design are not compatible with each other; the most diverse features are functional efficiency as warships and habitability to meet the creature comforts of those who man them.

Post-War to the Present Day

The ever-growing demand for electrical power made us realize that the ring-main system, as we knew it, could not cope with any substantial increase in generating capacity. The limit of capacity of individual generators with existing ring-main switchgear was 500 kW, and we now needed to think in terms of 1 000 kW generators at least for future cruisers, aircraft carriers —and indeed even for smaller ships—if we were to keep the number of generators in the system down to acceptable limits. To deal with these larger powers we had to consider the use of a voltage higher than 220 and whether it should be direct or alternating.

The number of motors in ships kept increasing (there are over 1 000 in a large carrier), and the replacement of the d.c. motor, with its commutator and brushgear, by the rugged squirrel-cage motor became an obvious and worth-while objective from the point of view of reliability and maintenance.

The position was now different from that in 1932, when a change to alternating current had last been considered and turned down, and with our war-time experience and the larger electrical installations we were able in 1946 to reconsider the question on a much broader basis. Furthermore, the ever-increasing demands to accommodate more and more operational equipment in warships made saving in weight and space of paramount importance.

The investigation showed that weight could be saved, even in a relatively small warship with a total of 1 000 kW of installed generator capacity, by adopting a 440-volt 60 c/s 3-phase a.c. system, with a proportionately greater saving in weight as the size of the electrical installation increased. Such a system had been in use in the U.S. Navy for some time. Although the possibility was considered, a voltage higher than 440 was not selected. With 440 volts for the basic system a single-phase voltage of 115 was adopted for lighting and small power loads. This voltage was chosen because the lamp filaments would be more resistant to mechanical shock and vibration, the design of miscellaneous small power-consuming devices was made easier, and there would be rather less danger from electric shock from small equipment supplied at that lower voltage.

The choice of frequency was not easy. Theoretically there is a case for adopting a frequency higher than 60 c/s in order to obtain further reduction in the sizes of motors and transformers, but the conclusion was reached that a wholesale departure from available standard designs would be very difficult to justify.

Investigations showed that a motor speed of 1 800 r.p.m. would meet a large number of requirements, and this, together with the advantage of 60 c/s in reducing the sizes of generators and transformers, made that frequency very attractive. Naturally, thought was given to adopting the widespread standard frequency of 50 c/s, particularly to make it easy to supply electrical power from ashore; but the lower speeds would have involved a quite unacceptable weight penalty. So, with the full support of industry when the facts were put before it, 60 c/s was selected. The added advantage of standardization with the U.S. Navy is obvious, and since we made our decision the other Nato navies have followed suit.

Although there is no alternative in cruisers and larger ships because the size of the electrical installation demands a distribution voltage higher than 220 volts, and therefore preferably an a.c. system, the case for alternating current in the smaller ships rested on:

(*a*) Reduction in weight.
(*b*) Considerable reduction in maintenance effort—an important feature in a small ship in which maintenance facilities are limited.
(*c*) Uniformity of design and operating practice with bigger ships.

An a.c. system is, of course, handicapped by its inability to provide, in a simple way, the speed control of motors which is readily available with direct current. This difficulty has been overcome to some extent by persuading the designer of the driven machinery that several speeds are not essential or, at the most, that a choice of two—obtained by pole changing—would meet his needs. For certain equipment, of course, a range of control of speed is essential and the extra weight and complexity have to be accepted.

The investigations which led to the adoption of alternating current in warships of destroyer size and above were made in connection with the design of a new class of cruiser and the *Daring* class destroyers. No orders were placed for that class of cruiser, but eight *Daring* class destroyers were ordered, and approval was obtained to build four with d.c. systems and four with a.c. systems so that a direct comparison could be made in ships where the advantages of a change to alternating current were marginal. It was intended to await operating experience with these ships before finally considering a wholesale change to alternating current; but before such experience was available it became necessary to design systems for three new types of frigates, and it was decided in 1948 to adopt alternating current for these and all future ships larger than minesweepers. Special considerations apply to minesweepers which favour the continued use of direct current.

The first large ships to have an a.c. system were the *Tiger* class cruisers, the construction of which had been suspended at the end of hostilities, because when it was eventually decided to complete these ships with modern armament and radar the consequent large increase in demand for electrical power had to be met by substituting four 1 000 kW a.c. generators for four 500 kW d.c. generators.

The recently completed aircraft carrier H.M.S. *Hermes* was dealt with in a similar way, and Fig. 9 shows the switchboard system installed in that ship. Within the limits imposed by a design not originally intended to accommodate a large a.c. system, the generators and their switchboards are grouped as units close to their associated boiler rooms.

When working out the details of the new a.c. systems it was necessary to lay down voltage regulation standards. It was decided to adopt a system in which the generator voltage is controlled to fine limits by using rapid-response automatic voltage regulators in association with appropriate exciters, and a cable system designed to give the minimum practicable voltage drop. Thus designers of individual items of equipment would have the benefit of a closely controlled supply. The alternative which was rejected was to control the generator voltage by more conventional methods giving a wider range of voltage regulation, and at the same time to allow a wider range of voltage drop in cables. This would have meant that, where necessary, the designers of certain equipment would have had to incorporate voltage-stabilizing equipment in their apparatus to provide the closer voltage limits.

It was decided that the voltage at the generator terminals should be maintained within the limits of $\pm 1\%$, and that the

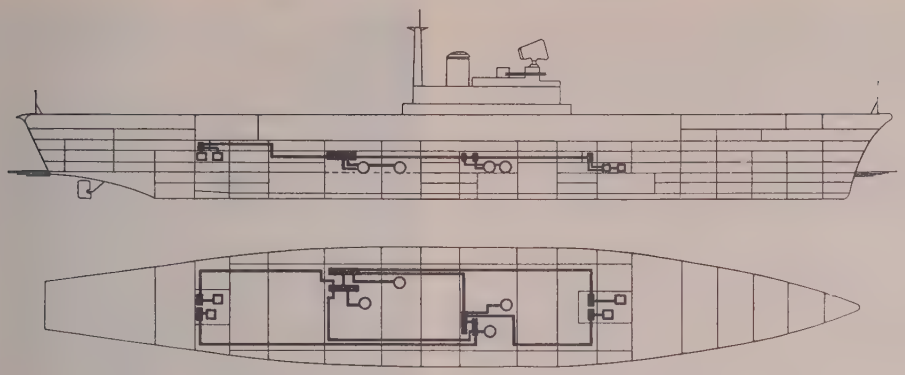


Fig. 9.—A.C. main supply system in H.M.S. *Hermes*.
440 volts, 3 phase, 60 c/s.
■ Switchboards.
□ 360 kW Diesel-generator.
○ 1 000 kW Turbo-generator.

argest voltage drop allowed on the system due to starting induction motors should not exceed 15%. Furthermore, after this voltage drop, recovery to ±1% was designed to be achieved within 0·3 sec. Later, it was found that a recovery time of 0·5 sec was acceptable. Frequency standards were also laid down.

Some converted supplies at higher frequencies are inevitable in a warship, but every effort is made to keep the amount of conversion equipment to a minimum. The higher frequencies selected are 400 c/s and 2 400 c/s. These are nominal and are derived almost entirely from generators driven by induction motors which produce a near multiple of 60 c/s. Direct current is still required for such services as degaussing, field excitation for special motors, computing and telephones. These supplies were largely provided by motor-generators in the first a.c. ships. Selenium rectifiers were also used and are still in use. They in turn are being superseded by silicon rectifiers, where appropriate, with a significant saving in weight and wild heat.

The 440-volt 3-phase system is a 3-wire insulated system with no earthed neutral. This differs from shore practice, but the essential feature in a warship power system is to maintain supplies in an emergency, and it is thus necessary to avoid tripping of circuit-breakers as a result of an earth fault on one line. Earth faults are indicated on the switchboard and are dealt with by the maintenance staff as soon as possible. The aspect of shock to personnel was not lost sight of when the all-insulated system was adopted. With alternating current a voltage over 50 can be fatal, and although by introducing an earthed neutral the possible voltage to earth is reduced, even this reduced voltage of 260 volts is highly dangerous in a ship. All 440-volt equipment is therefore designed to prevent accidental contact with live metal and is provided with 'difficult access' covers. The main switchboards, of which that shown in Fig. 10 is typical, are totally enclosed with dead fronts, and the breaker and switch-fuse units are withdrawable for servicing. It is very reassuring that so far we have had a casualty-free record.

Portable equipment is supplied from 115-volt single-phase systems which are unearthed. In order to increase the safety of such equipment, the circuits are taken from small transformers (not greater than 5 kVA) reserved for such use, or from reserved separate phases of larger transformers which have open-delta secondary windings. The ship's lighting and miscellaneous small-power equipment have their own transformers, so that the possibility of earth faults on the portable equipment socket networks is reduced to a minimum. A 50-volt supply from special transformers is provided for boiler-cleaning equipment because of the enhanced risk of shock when performing this work.

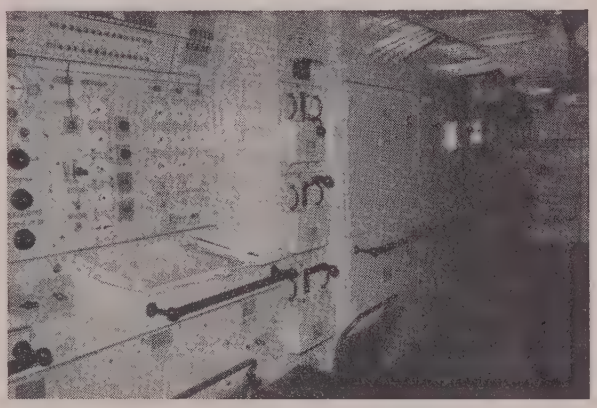


Fig. 10.—Typical a.c. switchboard.

It may be of interest to remark on a few of the special design problems which arose and which continue to demand our attention as a result of the use of alternating current.

The design of the circuit-breakers and motor control-gear for the first a.c. ships called for the closest collaboration between the Admiralty and industry because of the difficulty in making equipment of this type proof against shock from underwater explosions. For motor control-gear the problem could have been eased by using d.c. operation from rectifiers; but the aim was to save weight and space wherever possible and to provide simple, easily maintained equipment. Few firms were able to meet requirements when the first a.c. ships were being built, but that position has now been rectified and we can call on many more firms for this specialized equipment.

Single-speed squirrel-cage motors with direct-on-line starters are used wherever possible. In the first ships a few reduced-voltage starters were necessary, but the later ships have larger generators and direct-on-line starters can be used in all instances. A few of the larger motors are designed for low starting currents, thus avoiding the necessity for complicating and adding weight to the control gear with voltage-reducing devices.

The method of obtaining over-current discrimination with the

d.c. breakers in the ring-main systems was a well-tried one, and the same method was adopted for the hand-operated electrically-retained, and the electrically-operated, circuit-breakers in all a.c. ships to date, by using d.c. solenoids supplied from rectifiers. Short-circuit trials carried out in H.M.S. *Diamond*, one of the *Daring* class destroyers, showed that the system was not ideal for a.c. ships, and improvements have been incorporated in new designs of circuit-breakers for later ships to ensure more reliable discrimination and better protection of prime movers against severe overloads.

The introduction of alternating current brought with it the problem of voltage regulation of generators. With the relatively stable d.c. generator, pushbutton control of voltage by the switchboard attendant was acceptable, and in the d.c. era radar and other equipment requiring close-voltage a.c. supplies were catered for by motor-generators with carbon-pile voltage regulators. With a.c. generators some degree of automatic voltage control was accepted as being essential, and, that being so, it was decided to adopt a system of automatic voltage regulation which would meet the requirements of all basic-frequency equipment in the ship. The first a.c. ships used a thermionic voltage regulator which was duplicated, with means of automatic change-over from one channel to the other. The output was used to energize the control winding of a cross-field exciter. This system gave a voltage regulation of better than 1% with a recovery period of 12 cycles following the throwing-on of the test load of half full-load current at a low power factor.

The accelerated building programme in the early 1950's resulted in several generators of different outputs and several new designs of voltage regulators having to be put into service before experience with the earlier type of regulators had been gained. One of the designs incorporated a magnetic amplifier and this has given good service. In 1957 representatives from industry and from the Admiralty collaborated in the development of a standard design of automatic voltage regulator employing a single-channel magnetic amplifier. Power for the amplifiers is taken from an auxiliary 1 600 c/s permanent-magnet generator, which ensures continuous operation during the recovery period following a severe short-circuit. These regulators can be used with single exciters of conventional design to cover a range of generators from 150 kW to 1 500 kW.

Warship electrical systems are designed with a view to maintaining electrical supplies even though damage occurs in action. In spite of this, war experience proved the value of a system of emergency cables and connectors which can be used when damage to the permanent wiring is extensive. The problem of designing an emergency cable system for use at 440 volts a.c. under the conditions likely to prevail after severe action damage was no easy one. It has been solved by using plug-in connectors on the ends of the flexible cables, the connectors being fitted with safety sleeves which retract when the plug is inserted in the appropriate socket. The plugs can be inserted only in the correct phase socket, and are locked by an insulated key. Provision is made for emergency supplies to be taken from the switchboards by means of a special type of socket on the switchboard, and arrangements are made so that important equipment can be given an emergency supply through sockets adjacent to the motor starters or in the fuse panels supplying groups of equipment. It is necessary, of course, to provide special watertight bulkhead terminals so that the emergency power can be taken through the ship without having to leave watertight doors open. Coils of prepared cable, fitted with the protected plugs, as shown in Fig. 11, are dispersed throughout the ship. Portable fuse panels and transformers for lighting are also provided.

There is no doubt that the decision to adopt alternating current

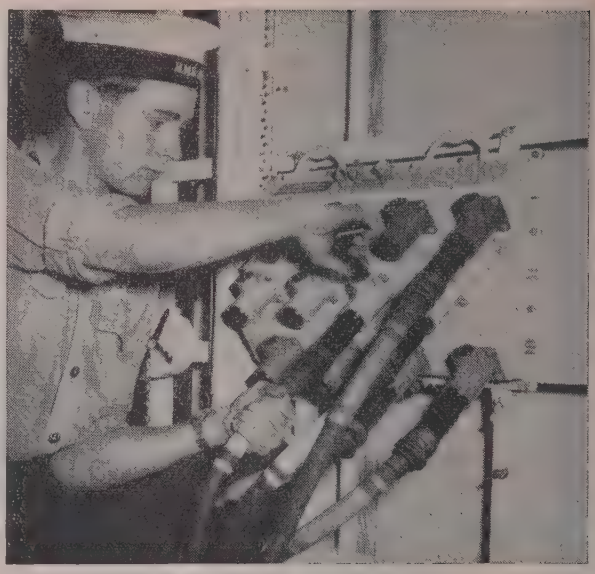


Fig. 11.—Emergency cables.

was right. Admittedly, many problems have arisen and not all have been completely solved. Motor reliability is not yet all it should be, but new insulating materials will help us towards our objective of greater reliability.

Before concluding this review of post-war progress, it seems appropriate to make some reference to the selection of prime movers for driving generators. In this aspect of warship design, as in many others, the requirements of peace and war are conflicting. In peace it is necessary to reduce watch-keeping in harbour to a minimum so that it is desirable to let steam die down and change over from steam turbo-generators to Diesel-generators. Thus the peace-time role of the Diesel-generator is to maintain supply in harbour.

In war it is normally necessary to keep up steam even in harbour, which means that the steam turbo-generators can continue in use. The function of the Diesel-generators then becomes that of providing a standby or auxiliary source capable of providing sufficient power, in the event of all steam being lost, to supply the salvage load, with enough left over for at least the anti-aircraft armament so that the crippled ship may still defend herself. These separate functions are not always compatible, and as in other aspects of warship design the best compromise has to be reached. The gas turbine is capable of fulfilling a dual role, and with that in view some of the generators in our latest ships—the guided-missile destroyers and the general-purpose frigate—are driven by gas turbines.

The demand for electrical power in warships has increased by leaps and bounds. Fig. 12 shows the growth of generating capacity in various types of ships over a number of years. Part of the increase in later years is admittedly due to a greater acceptance by all concerned of the need for more reserve than was usual before the war. Apart from the obvious growth in the use of electricity for motor-driven auxiliaries, particularly since the advent of alternating current, there has been a steady increase in the operational power demanded for weapon systems, radar and radiocommunication. The domestic electrical load continues to grow, ranging from air conditioning to drinking-water coolers. The modern sailor expects reasonable amenities and to be able to use his own radio set, record player and electric shaver. In the general drive to improve amenities in warships, electricity plays a big part.

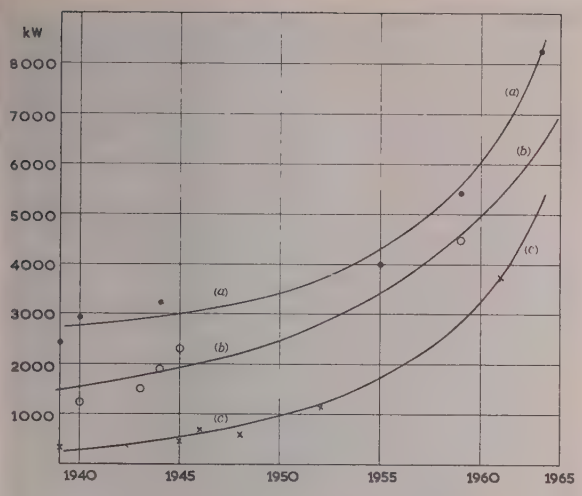


Fig. 12.—Growth of generator capacity.
(*a*) Aircraft carriers.
(*b*) Cruisers.
(*c*) Destroyers.



Fig. 13A.—Petty officers' accommodation in H.M.S. *Hermes*.



Fig. 13B.—Petty officers' accommodation in an older ship.

The electrical equipment in a modern warship encroaches on all compartments, but modern practice demands concealment as far as possible in living spaces. Fig. 13A shows petty officers' accommodation in the *Hermes*, where electrical installation is not so much in evidence as in earlier ships, of which Fig. 13B is a good example.

In aircraft carriers there is a heavy demand for electrical power at various voltages and frequencies in the aircraft hangar and on the flight deck for servicing aircraft. Also, the electrical equipment associated with airborne radar and missiles requires to be energized for long periods whilst awaiting take-off to avoid unnecessary running of the aircraft's engines.

In this post-war section I must make some reference to other improvements and progress in various aspects of naval electrical engineering. A much higher standard of demagnetization is now necessary in minesweepers to ensure safety when sweeping in shallow waters. Even the eddy currents induced in the metal frames of composite wood and aluminium hulls when rolling in the earth's magnetic field are capable of producing fields which can fire a sensitive magnetic mine. These unwanted eddy-current fields have to be compensated. Detector coils, fitted at the top of the mast, provide signals which, suitably amplified, initiate compensating currents in the ship's degaussing coils.

The development of the electrical analogue computing systems for modern anti-aircraft gunnery is an outstanding example of post-war naval electrical engineering. A distant aircraft target is detected and held in the sights of a director or its modern equivalent, a tracking radar set. The movements in elevation and training of the director or radar as it follows the moving target provide data from which the present position, speed and direction of the target can be computed. Solving further equations will predict its future position, and equating these to yet further predictions of where a shell will be at a given time after it is fired will yield, if the calculations are correct and completed in time, the necessary information as to where to point the gun so that the shell and the target will meet. It is also necessary, of course, to make accurate allowance for other factors, such as the rolling and pitching of the ship. A solution to this problem was reached by developing electrical analogue computers capable of continuous computation and prediction. This was a long and complicated task, but it was successfully accomplished and has resulted in gunnery accuracies hitherto unattainable.

To facilitate production and maintenance of such a system, it was divided into sections and further subdivided into a large number of individual plug-in units. Although a comparatively large number of amplifiers were required, it was found possible to confine them to a few basic types, which were arranged to conform to common dimensions, so that all would plug into a common rack.

Internal communications play a vital part in the running of a warship. They range from straightforward 500-line automatic telephone exchanges of the G.P.O. type used for administrative purposes, and installations for entertainment, to a series of operational communication systems. The most complex of all permits aural communication in an ambient noise level of 130 dB. The most obvious example of the need for this system is the flight deck of a carrier when the aircraft jet engines are running. The problem was solved by radiating signals from a loop round the flight deck. These are picked up by a miniature transistorized personal receiver, the output of which is fed to a telephone-type inset in the earpiece of a noise-excluding headset worn by all personnel concerned.

The scale of an internal communications installation in a modern aircraft carrier may be gauged from the fact that there are over 800 telephones and well over 600 loudspeakers. An

experimental closed-loop television installation has recently been completed for the briefing of air crews.

Since 1945 a major contribution to saving in weight has been made in cables by replacing the lead-alloy sheathing with a polychloroprene sheath—30 tons weight were saved in a destroyer of the *Daring* class. The removal of the metallic screening, however, raised doubts whether the interference with W/T reception would be unacceptably increased. Careful attention to suppression of interference at its source, and the use of 'in line' capacitors as filters, has avoided any increase in radio interference.

A more recent change resulting in a further saving in weight has been the introduction of silicone rubber as the insulant for all cables. This change was made possible by the co-operation of the British and American cable manufacturers after a detailed examination of American practice in this field. One of the advantages is that the residual ash of silicone rubber, after being subject to fire, continues to act as an insulant so that circuits continue to function even after compartments through which the cable are run have suffered damage by fire. The combination of polychloroprene sheathing and silicone-rubber insulant has made possible cables of reduced diameter and weight so that installation is greatly facilitated. The saving in weight and in the space occupied by cables is also valuable. The value of the change is well illustrated by Fig. 14.



Fig. 14.—Cable trunk.

A further recent improvement has been the introduction of a hanger system for the support of main runs of cables. This replaces the traditional carrier-plating system and has the advantage of simplifying installation, saving weight and providing easier access to the ship's side for painting. Fig. 15 illustrates the obsolete carrier-plate installation, and Fig. 16 the new cable hangers.



Fig. 15.—Carrier-plating system.



Fig. 16.—Cable-hanger system.

Consequent upon the ever-increasing numbers of cables which have to be installed in modern warships, a new form of water-tight bulkhead gland has had to be developed to permit more cables to pass through the area available in bulkheads. This new gland takes the form of a box welded into the bulkhead through which the cables pass. The box is then sealed up solid by filling it with a quick-setting rubber-like compound. Such boxes are shown on the left-hand side of Fig. 17.

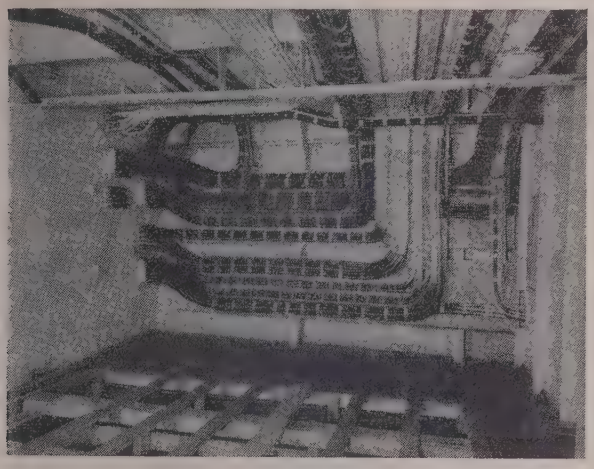


Fig. 17.—New method of passing cables through bulkhead.

It will be readily appreciated that the increase in the use of electricity for power purposes in ships results in a corresponding increase in the number of power cables to be installed. What is perhaps not so obvious is that there is an equal weight of cable used for operation and control purposes in the various weapon systems, including the associated radar, asdic and internal communications. The installation of the cable system for such services in H.M.S. *Eagle* involved making half a million connections. Fig. 18 shows the operations room in a frigate while cables were being installed.



Fig. 18.—Operations room, showing the false floor.

I shall complete this post-war section with a brief survey of the special electrical problems associated with the submarine.

The war was fought with submarines in which, although there had been detailed improvements, the electrical system by which the vessels were propelled when submerged were substantially as they had been for twenty years. The main battery, in two or three sections each of 112 lead-acid cells, gave a nominal voltage of 220, and was only sufficient to permit maximum submerged speeds of 9 knots for periods of less than one hour. Speeds to permit reasonable submerged endurance had to be as low as 4 knots. The circulating air in the main motors was water cooled, and switchgear comprised open-type hand-operated knife switches protected by fuses. The limitation on submerged speed and endurance was a very serious handicap to submarine operations, and after the war great efforts were made to improve the underwater performance of new designs of submarines.

The first attempt made use of the Walther system, in which oxygen is stored in the form of highly concentrated hydrogen peroxide (high test peroxide) and used as the oxidant for burning oil when submerged. Two experimental submarines with this system are now in service, and until 1959 held the world record for underwater speed. The machinery, however, is complex and requires much maintenance. H.T.P. is a very dangerous and expensive liquid, and high speed endurance is limited to a few hours by the amount of H.T.P. which can be carried.

The second method of improving submerged performance is by increasing the capacity of the battery. War-time built submarines of the 'T' class were cut in two and lengthened. The increased space within the hull was used to accommodate a fourth battery section and two additional double-armature main motors, which were installed so that there are two motors (four armatures) on each of the two propeller shafts. For high speeds two battery sections are connected in series to give a nominal 440 volts. New cam-operated switchgear for the control of this equipment was developed.

The 'T' conversion, as it was called, was a stop-gap, and in the new *Porpoise* class a radical departure from previous design practice was made. There is one twin-armature main motor on each shaft, and these are used to propel the vessel on the surface as well as submerged. The whole power of the ship is controlled from one position, and this was an innovation in submarine electrical engineering practice.

For maximum speeds the batteries are connected all four in series to give 880 volts, and for ordinary working the system voltage is 440. Motor-driven cam-contactor switchgear is used, and special attention has had to be given to fault protection by means of high-speed high-breaking-capacity switchgear. To test the equipment, one of the largest-capacity d.c. short-circuit-testing installations in Europe was built at the Admiralty Engineering Laboratory. For transmission of power through the boats between batteries, main generators and main motors, copper busbars insulated with moulded micanite and metal-enclosed are used.

In electrically propelled submarines the battery determines the limits of performance, and by careful attention to design, thinner plates and improved separation, the capacity of the standard lead-acid cell has been increased from 4 750 Ah, at the 5-hour discharge rate, at the beginning of the war, to 6 560 Ah at the present time. Despite this increase in capacity an operational life of 300 cycles is still obtained.

There are, however, other problems for the battery designer besides specific ampere-hour capacity. Hydrogen gas is constantly being evolved from lead-acid batteries, and a mixture of 4% of hydrogen with air is highly explosive. It has been found possible to reduce the open-circuit evolution of hydrogen by the development of battery grid alloys with low antimony content. Research is continuing in an attempt to produce batteries completely free from antimony which will not evolve any hydrogen at all on open-circuit, and at the same time will eliminate the production of antimony trihydrite (stibine), a very toxic gas.

Water cooling has been adopted for the latest high-perfor-

mance batteries, and a further development is electrolyte agitation to permit shorter charging times.

Battery containers have been continuously improved to withstand shock resulting from depth charges. Ebonite containers were first superseded by laminated plywood with a rubber lining, and these in turn have been replaced by rubber-lined resin-bonded glass-fibre boxes.

The latest method of improving submarine performance is the introduction of nuclear propulsion plant which, by providing virtually unlimited power and endurance, will revolutionize submarine warfare. Indeed the submarine becomes at last a true submarine and not just a submersible vessel. Although there are many special problems, the electrical installation in a nuclear submarine in fact becomes more like that of a modern surface warship with the addition of an electric drive of small power for emergency use. Also, a nuclear submarine must still have a battery for starting up and emergency standby, although this is reduced to one section of 112 standard submarine cells. Because of the possibility of prolonged submerged operation the problem of hydrogen evolution assumes even greater importance than hitherto, and a further complication is introduced by the danger of accumulating stibine. The efforts to develop a reliable battery with antimony-free plates have therefore been increased.

Like surface ships the submarine has to accommodate an increasing amount of electronic and servo equipment for weapons, asdic and other purposes; and to this is being added, in the atomic submarine, new problems of reactor control and instrumentation. Space for all this equipment is difficult to find, but in the application of the semiconductor in its various forms lies hope for some easing of problems of space, reliability and performance.

The Future

I have attempted to review how electrical engineering has been applied to meet the requirements of the Royal Navy, and how it has developed over the last three-quarters of a century. I propose to conclude my review by very briefly attempting to forecast what further changes we may see, perhaps in my lifetime.

In the personnel field, I think it will be inevitable that the pattern of increasing specialization in design of equipment and installations must continue to an even greater degree. Both the serving naval electrical engineer and his civilian counterpart in the supporting services ashore will need to be of the same high standard or even higher than to-day. With the inescapable drive to reduce staff to the minimum, the need constantly to review organization methods to streamline and eliminate all unproductive work will continue.

In the material field, thanks to the close co-operation that exists between the Admiralty and the electrical industry, knowledge of new discoveries and developments becomes available at a very early stage so that possible naval applications can be kept in mind. Constant application of judgment will be increasingly necessary to decide when new materials and devices can be adopted for warship installations. The biggest drive in future years will continue to be for increased reliability and reduction in size and weight in every field of application. Already in the electronics field this has led to micro-miniaturization and the adoption of semiconductors for many applications. In the ever-broadening sphere of the semiconductor, possibilities range from microamperes to kiloamperes, embracing minute amplifiers and bulk power conversion. He would be a rash man indeed who tried to forecast where this trend will reach in any field.

Generation of power at frequencies higher than 60 c/s and voltages above 440 may be found necessary. Production of power by such methods as the fuel cell and thermo-electric generators may become practicable in the not too distant future, though much development work still remains to be done.

Nuclear propulsion of submarines has already been proved; but if it can be justified for surface warships it will present problems which have still to be tackled. The electrical engineer will be involved in the development of faultless and foolproof control systems, and in novel designs of auxiliary electrical machinery, capable of working continuously under very adverse conditions without risk of breakdown.

These and similar problems which are associated with missile installations will keep my successors in the naval electrical engineering field fully occupied, and will exercise not only their ingenuity, but also that of their colleagues in industry and elsewhere, whose enthusiastic co-operation will be just as essential in the future as it has been fruitful in the past.

In conclusion I wish to place on record my appreciation to the Board of Admiralty for permission to write this Address. I also wish to thank those authorities who so kindly provided illustrations and models, and in particular the Maritime Museum at Greenwich.

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SUPPLY SECTION: CHAIRMAN'S ADDRESS

By J. E. L. ROBINSON, M.Sc., Member.

'THE DEVELOPING ENGINEER'

(ABSTRACT *of Address delivered 19th October*, 1960.)

I am concerned with three interpretations of my title and text. First, the evolving position of the engineer and his responsibility to society; second, the growth and unfolding of his own role and personal outlook; and third, the narrower meaning of the engineer specifically concerned with the development of his product.

Social Aspect

Towards the social aspect, much abler authorities than I are increasingly turning their attention. In this theatre in the past twelve months, last year's President, Sir Willis Jackson, my predecessor, Dr. Mortlock, and the Graham Clark Lecturer, Sir Hugh Beaver, in my own hearing, have all contributed to a new evolving philosophy of where the scientific and technical man is going and where he must go. Is he shouldering adequately his growing humanistic responsibility? Is his training best directed towards his doing so, and is the rest of society sufficiently aware of the increasing part that this man is being called upon to play? It is healthy and encouraging that this self-criticism and constructive thinking is being so urgently engaged in by our leading members.

Much of this attention is being directed to education at the university and technical college level, whence an increasing number of our future leaders can be expected to come. There is recognition that our present scientific and technological courses are too specialized and too narrow, and that they insufficiently develop the mind and character on the humanistic side. There is a growing advocacy towards including more widely educative subjects in the technical courses and also towards inclusion of training for management. This last is, however, of its own nature specialist enough, and while I am all for these steps I do not feel that they go deep enough.

I am with those who feel that the roots of something we are missing go back to school days, that it is there that the most fateful steps towards specialization are taken. Sympathetic awareness of the ways of minds and of peoples should be developed in the more relaxed years of evolution from childhood, and study of past experience and humanistic subjects should continue in a generous measure right through the school curriculum till the leaving stage. It is on that sort of foundation that such subjects as management studies at the university stage can most profitably build.

In some degree and in some places much of this is practised to-day: what is wrong and what leads to the shortcomings of which we are conscious is the inadequacy of its scale and extent. The same arguments hold for increasing the scientific training at school of the non-scientists. If we accept that the hours of school work are already optimum, a consequence of such steps would inevitably be some lowering of the standard of specialist training at the school leaving stage, and correspondingly the need for university training to commence from a lower level. To me ultimately the right solution would seem to be along the lines of those who advocate four years rather than three at the university in order to realize the objectives of a sufficient specialist training against a sound and wider general educational background.

The growing importance of these considerations not only to us engineers but also to the community is markedly illustrated—again at the university level—by the figures Sir Willis quoted, which showed that the scientific content of our universities has already grown from 26% before the war to 38% to-day and should reach 44% in five years' time. This will inevitably have growing impact on those more cloistered communities themselves and presages the increasing influence those with scientific training can be expected to have on society in the generation ahead.

And is there sufficient realization on the part of the community of this portending technical growth? I think there is much encouraging evidence that there is. Dr. Mortlock was concerned that we should avoid going to the extremes of Russia's materialistic society, where the technical men play so predominant a part. All that I have referred to above seeks to steer away from that danger. It would seem, moreover, that the engineers' own products of radio and television have come in time to effect a growing awareness and spreading of appreciation, not only of music, history and the arts, but also of the exciting unfolding story of scientific development and the exploitation of the secrets of nature to increase the living standards and wellbeing of mankind.

Individual Aspect

While it is not easy to be objective in generalizing about the broader social picture in which we are subjectively involved, it is even more difficult to try and appraise the growth and unfolding of an individual engineer's own outlook where the assessment must be done against the moving background of personal experience. But with this in mind I still feel sure that the deep change I myself am aware of in the outlook on technical evolution is not all on account of my growing years but has a general significance.

My generation came to engineering at the beginning of the 'thirties when the slump conditions were the reverse of stimulating. Looking back I cannot recall being excited about the unlimited potentialities ahead. I do not mean that we thought that development, like history in the book of the period, was at an end, but I do not think that the 'break-through' concept had taken root in our philosophy. So much of the equipment within our reading and experience was slowly evolving in efficiency and size, but in power engineering so much of that evolution seemed very slow and asymptotic in nature. The limitations of conducting, magnetic and insulating materials seemed to be largely taken for granted.

There were, of course, notable exceptions in other directions which were viewed with interest, but not in my case with any deep appreciation of the new outlook to which they were the pointers. Cockcroft split the atom, rather more attention than since the writings of Jules Verne and H. G. Wells was given to the possibility of reaching the moon, and Fleming's valve advanced a long and spectacular way in performance, but even

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it appeared to be coming up against a stone wall imposed by the limitations of transit time on its development for higher frequencies. The aeroplane was getting bigger and more reliable, and was going faster, but so much of the general tenor was of development of devices proceeding logically along their preordained lines and then slowing down against the mounting effect of limitations inherent in their conception and the available materials.

To me at least the awakening of a different philosophy came in the war period. The rapid birth and development of radar, the exploitation of the very limitation of the Fleming valve to utilize transit time as the basis of the operation of the magnetron, the successful development of the internal-combustion turbine, the German dirigible rocket and the culmination of the Curies' and Cockroft's work in the atomic bomb, all shook the complacency of the older view.

To this newly oriented philosophy the developments of the past decade have merely topped confirmation with emphasis. The bomb becomes the fire for the boiler: the fission reaction becomes the trigger for the fusion one; radar checks the distance to the moon and opens the way to the radio telescope to bring in more information about the universe; the crystal and whisker become the phenomenally improved rectifier and lead to the transistor; the fusion knowledge leads to the currently mounting attack on the thermonuclear reactor and the vision of the direct generation of electrical power from matter; the sound barrier is conquered by manned machines; the rocket gets away from it all and the moon is reached and passed.

Confronted with this widespread and accelerating advance, what changes are not possible and to what rocks of our experience can we safely cling while we retake stock of our accepted situation? It all leads to an open-mindedness about the likelihood of inherent great change, and it encourages an energetic and continuing re-examination of previously accepted limitations. It encourages untrammelled speculation about what would happen if one or more limitations were obviated by even fantastic means. It prompts an eager searching for snowballing consequences which might justify and repay the taking of the fantastic steps. It promotes impatience to achieve the end once it is desired.

The Development Aspect

This brings me to the domain of engineering development, the third aspect of my title which I want to dwell upon. You will realize that I see all engineers as in some respect engaged in development—anyone who contributes to a better way of doing something or who through an open-minded outlook co-operates with others who are guiding such work. It is not given to many of us to invent or to conceive great innovations, but inherent in my understanding of technical development are all orders of contribution towards a better solution. We can all study systematically or otherwise the way to progressive improvement; the spectacular and the break-through experience comes to a very small number of workers.

At one end we have the almost routine increasingly intensive investigations into the basis of design which the computer has opened up to us—cases where a few per cent gain can be squeezed from factors where the designer previously had to depend largely on his judgment. At the other end we can get closer to grips with the known limitations, study the boundary conditions, seeking always for approaches which fit in better with the natural laws and are less entangled in conflicts and compromises, always hoping for a link up of the logical study with the more intuitive processes.

Basic Materials

Before reviewing in this way the present outlook on some of our basic apparatus it is appropriate to consider the conducting, insulating and magnetic materials which dominate the practice and economics of our technology. It is the electrical aspects of these materials that I am concerned with; for, on the whole, advances in the physical characteristics of our constructional materials are likely to be secondary rather than primary in their impact.

In some ways the development of the magnetic material is the most advanced—at least in the closeness of approach of working flux density to the ultimate saturation density of the best of the known materials, iron, in the region of 22 500 gauss. A decade ago transformers were still mostly operating in the region of 13 000 gauss. With the development of grain-oriented material—pioneered by one of our members—it can now be economic to work as high as 19 000 gauss, and, but for the necessity for allowing for over-voltage conditions, a density of 20 500 gauss has in my own experience been practicable for large power transformers. This ability to operate within 10% of the known limit represents a big step forward, but there is still much to be achieved. There is every reason to expect that better control over the metallurgy will yield a more homogeneous material whose hysteresis loss, magnetostrictive and noise performance will be further greatly reduced, although possibly at some economic sacrifice of ultimate working density.

The development of insulation is too large a subject to do more than touch upon here. Despite all the advantages of the growing number of synthetic materials, it is a fact, frequently commented upon, that one of the earliest materials—oil-impregnated natural-cellulose paper produced from wood pulp or cotton—is as yet for high-voltage work unsurpassed in respect of combined mechanical, electrical, thermal and life qualities. And yet it is a very imperfect material. In its construction almost inevitably there is a lack of perfect uniformity in the quality of its fibres, and some admixture of blemishes, of foreign matter or less digested fibres always occurs. In thin sheets these give it only a statistical value as insulation and recourse has to be had, as in paper-dielectric capacitor practice, to the lamination of sheets to minimize the chance of a weak path occurring through the whole. In thicker forms this protection is automatically obtained but at the expense of the effective gradient at which the material can be worked. When one compares the maximum a.c. stress of some 150 kV/cm at which h.v. cables can be operated with the levels of upwards of 1 000 kV/cm which pure materials can withstand, it seems reasonable to expect that it is only a matter of time before our chemists enable us to make a big advance here.

It may even prove that better insulation with the conflicting property of better heat conductivity will be developed, but even if this does not happen, at least the snowball effect of reducing the thickness of the dielectric will greatly affect the economics of this fundamentally unsatisfactory compromise which dominates so much of our apparatus.

And what about the conductor whose resistance bedevils all our supply equipment? The star performer, silver, is so little ahead of its runner-up, copper, that no great economic advantage stands to be made this way. I do not suppose there is any basis for hope that a better conductor at normal temperatures will ever be found. But is it not possible that we shall succeed in avoiding the restrictions and exploiting the advantages of superconductivity and get control of the situation that way? Great advances are being made in development of the necessary cooling pumps, and can we not look forward to circulating liquid helium through the conductors of a cable or around the windings of a transformer? When we remember that in the last few years experimental equipment has been developed in which temperatures of the order of millions of degrees Celsius

re contained, is not there some encouragement for expecting hat the problems of operating at 20 or so degrees above absolute ero will be surmounted? Achieve this and the effect on our pparatus is to be measured not in tens per cent but in orders of nagnitude.

At least one, and that the biggest, unsatisfactory compromise f our present-day techniques would disappear—we would enter . field where insulation was required to be simultaneously good oth electrically and thermally. This condition would apply to he whole of the insulation, whereas the offsetting disadvantage f the conductor being required to be good electrically and bad hermally would apply only in the region of the end connections.

Cables

When we pass from the materials to, perhaps, our simplest equipment, the power cable, many of the foregoing considerations apply with full force. Surely sooner or later we shall have dielectrics which will run at several-fold greater gradients and the cable as we know it to-day will carry proportionately more power. The fact that already with present techniques the power rating is increased some three times or more with d.c. as against a.c., illustrating the simple truth that a.c. makes inefficient use of cable dielectric, together with the elimination of distance-correction problems, is a strong pointer to where future progress must be sought.

With deference to many of my colleagues, surely the long-term future of all power transmission must lie with the cable; it is so much more flexible and neater and natural a method. Long-distance transmission lines to-day may on first cost be superior to cables by a factor of 15 or so, but none the less there is unmistakably something very nineteenth century about them and I feel that with further developments of cable dielectrics they will someday become outmoded.

D.C. to A.C. Conversion

Of the problems confronting our supply industry the conversion of high-voltage direct current to alternating current is one whose full solution could have very far-reaching effects. The work of Dr. Lamm and his team demonstrated the technical solution of the problems, and the Russian project is carrying it to a higher-power longer-distance stage, but it is fair to say that, although we have the technical solution, we have not the economic one—so much of the potential gain being offset by the cost of the complications involved. It is natural for us to look hopefully towards the spectacular development of the semiconductor rectifiers and the transistor, but whether by this means or another the record of contemporary developments encourages us to hope that the solution will only be a matter of application and of time.

Switchgear

And where does switchgear stand in this catalogue; is the circuit-breaker all that it should be? There is, of course, something essentially brutal in the 'breaking' of a circuit. Although it works it does not seem the right way. We turn off water relatively slowly to minimize the inertia effect, but to do this to large-power alternating current, with present techniques, would involve extensive and uneconomic electromagnetic equipment. The brutal method works, and our colleagues who design it are victoriously carrying its performance forward to meet the mounting demand for greater interrupting capacity.

But if the method of breaking alternating current stays with us, what will the interrupting medium be? In some ways it seems odd that such dissimilar media as air and oil lead to similar solutions economically. Will it turn out that vastly higher gas pressures or higher vacua will be a better solution, or will developments of semiconductors become the answer? Alternatively, will the highest-power switching requirements be fully provided as a by-product of d.c.-to-a.c. conversion equipment? I repeat that to me it does not seem likely that the present method will be the ultimate.

Generators

Before direct generation of electricity from chemical or nuclear fuel is achieved, there is still a long career ahead of the alternator. Notable advances are currently being made with the development of higher ratings, and it is arguable that the alternator has reached nearer to its ultimate form than has the transformer, but some of the considerations which I shall refer to on the latter have a parallel application.

Transformers

Having ventured comment on other people's affairs, I now turn to my own—the power transformer. This has, of course, come a long way since the time of Faraday's experiments or even since the original Ferranti Deptford designs, but even so the change has been only a slow evolutionary one. The essence of the transformer lies in its windings, and just as with transmission lines there is still a strong nineteenth-century flavour about them. In all forms, core or shell, helical, disc or layer, the windings are relatively complicated and depend on a high element of craftsmanship and the tendency is towards greater rather than less intricacy.

The magnetic properties of iron entail the economic transformer having many turns, a voltage per turn of two or three hundred volts being typical of the larger units. Evolution has manifested itself largely in the shape and make-up of the conductor and the method by which the hundred or thousand turns are disposed. But, as with the cable, the materials for the winding still remain basically copper, natural cellulose and oil, and a great deal of design and winding skill goes into each transformer. One therefore asks, Is this the final and ultimate and most logical way in which transformers should be made—is this slowly evolved technique the most natural?

The weight or the volume or the cost of the transformer is predominantly the sum of the corresponding quantities of the iron and copper circuits. The more effectively the window in the conductor circuit is filled with magnetic material, and the more effectively the window in the iron circuit is filled with conductor, the more economical is the transformer. Magnetic space factors of the order of 85% obtain, and some further improvement will be progressively achieved. Conductor space factors, chiefly owing to the demands of insulation and cooling, are more regrettably low and on large units are of the order of only 20%. The relationships are rather complicated, but in approximate terms the weight of the optimum transformer is inversely proportional to the 3/5 power of the conductor space factor. Raise this factor from 20 to 80% and the weight and cost will come down to 40% of the present, or alternatively ratings four times higher will be achieved for the same weight.

When you examine in detail along these lines to see what is being done with the 80% of space that is not filled by conductor, it is very noticeable that the conflicting factors bearing on the precise disposition of the conductors lead to multiplication of the volume of insulation compared with the minimum that the essentials appear to demand. Two border-line simplifications are conceivable, and one of these, where each turn is of width nearly equal to the length of the core leg and of a few mils radial thickness, immediately seems to be a natural. At least, so I thought when I first reasoned to it some years ago, and

further reflection confirms this and suggests that it is the way nature intended transformer windings to be made, and that, by happening to make his first windings with wire instead of foil, Faraday has left us to enmesh ourselves with it, and we have been on the wrong tack ever since!

In the general case such a winding will be containable within a cylinder whose inner, outer and end surfaces are at earth potential. Fig. 1 shows an axial cross-section of such l.v. delta-

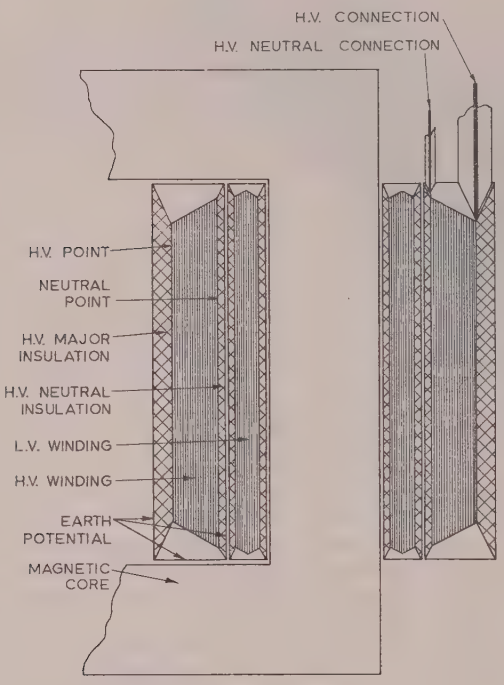


Fig. 1

connected and h.v. star-connected windings. In the case of the h.v. winding, starting from the inside, continuous sheet insulation, with capacitance control coatings at suitable intervals, is wound on to a mandrel to the value required for the neutral. The winding is then formed from a continuous conductor foil and a continuous sheet of insulation of a few mils thickness, the widths being gradually tapered to provide the required contours at the cylindrical ends of the winding. On top of this is formed from sheet insulation another capacitance-controlled cylinder to the value required by the h.v. voltage. The contours at the ends are shaped in accordance with the voltages to give in the oil-filled vee spaces controlled uniform gradients whose equipotential lines are parallel to the end surfaces of the winding cylinder. This enables the leads as shown on the right-hand side of the section in Fig. 1 to be taken out through graded capacitor-bushing-type connectors whose outer surfaces are at earth potential. Cylindrical axial cooling ducts are included in the winding at appropriate intervals, and these carry only the voltage of a single turn. Tapping leads are brought off as required from near the neutral end.

Such a winding construction yields a number of advantages, of which the more prominent are:

(i) All the solid insulation is stressed at a uniform value, and its volume appears to be the minimum for the proportions of the winding. In the liquid insulation the gradient is also controlled at a uniform value. There is no 're-entrant' insulation as with conventional windings.

(ii) The distribution of impulse voltage is very closely linear, like the power-voltage distribution. The normal local reinforcement of insulation to accommodate non-linear distribution is therefore not required. The winding has a greatly increased effective capacitance under impulse conditions.

(iii) The current in the windings is free to dispose itself for perfect ampere-turn balance, so that axial mechanical forces—which are a major limitation with conventional windings—do not arise.

(iv) The conductor being thin in the radial dimension, the normal cause of conductor eddy-current loss virtually does not arise. Calculation and experiment show that neither is eddy-current loss at the axial ends of the winding a problem.

(v) Cooling ducts are in the body of the winding and do not limit the working gradient in the major insulation. The ducts are simple axial channels and do not interrupt the axial length of the winding, and forced oil-flow superimposes on the natural thermo-syphon action.

(vi) Tapping windings are homogeneous with the main winding in respect of ampere-turn balance and impulse distribution.

In summarizing these points it is apparent that several of the unsatisfactory compromises in the conventional winding are sidestepped, and the fact that the whole design problem simplifies down from the previous trial-and-error solution to virtually an explicit relationship also seems significant and is certainly welcome.

Why then are transformers still made in the same old traditional ways? Partly the answer is that, although such a solution disentangles us from a whole host of conflicting limitations, it confronts us with new problems of a totally different kind. The new ones are not even electrical but are primarily of a constructural and manufacturing control nature. Of what materials are we to construct the winding and how are we to hold the whole together?

The conductor will probably remain copper, although the ease with which aluminium can be given a thin tough insulating-oxide coating gives it a new claim for consideration here. For a working voltage of a few hundred volts and an impulse voltage of the order of 1·5 kV, it is conceivable that only a mil or so of suitable dielectric will be necessary between turns. There will, however, in all be several acres of such insulation on a large transformer, and being equally stressed throughout it must all be entirely free of fault. Therein lies the first problem. So great, however, is the saving in insulation in comparison with the conventional winding that even with 5 mils of insulation between turns the new method compares favourably.

But what dielectric are we to use? Should it be sheets of impregnated paper, or should they be of plastic or should the dielectric be formed or coated on to the conductor? And if we follow existing techniques employing thin insulation do we laminate, at least as a precaution? And with any of these how do we hold or stick the lot together so that the windings will carry their own weight through the thermal cycling of 30 years or more?

Although the immediate path to successful service application is not clear, an attractive longer-term result can be foreseen. The principal raw materials for the winding would simply be a quick-setting liquid adhesive insulation and copper billets. The inner major insulation is formed on a removable mandrel by continuous application of a thin coating of appropriate width until the required radial thickness has been built up. Conducting capacitance-control coatings are printed in during the process. The copper is electroplated on to a mandrel to the required thickness of varying width. The foil so formed is immediately

eeled off, the start connector lead is attached and a mil or so f insulation is applied and set. The insulated foil is recoated ith insulation, this time as an adhesive, and while it is still wet wound on over the inner major insulation. As the winding roceeds any necessary tapping connections are made to the foil nd the cooling duct separators are also fed in. After the end onnector lead has been attached, the outer major insulation is ound on similarly to the inner. On the adhesive being set, the inding is complete. The coating and winding may well be arried out *in vacuo*.

Well, that is how I think the transformer winding of the future hould be made. The process would be near continuous, the igh labour content and craftsmanship would disappear, the roduction time would come down from weeks to hours, and he weight and cost would be much less, the reduction to as low s 40% of the present values that I mentioned earlier being uite feasible. The reduction of cost would be of the same order.

Before leaving the subject I would draw attention to one other orollary which could follow. A cylindrical metal tank with an nsulating seam would be formed to enclose the whole winding ssembly of one leg. All connections would be taken through he tank ends by sealed cable-type connectors. The cooling ystem would be made individual to each leg, and this would ssist in maintaining the highest degree of cleanliness. Assembly on site of large transformers would be from three such complete sealed winding groups and a separate enclosed magnetic core also with its own cooling system. Only this last, which is the least susceptible to contamination, would need to be disturbed for site assembly. This would open the way to the practicable use if required of transformers of several thousand MVA rating.

Conclusion

I feel that the mid-twentieth century has a claim to be, if not a turning point, at least one of marked upward inflection in the changing concept and pace of technological development, and that the greater events around us should stimulate us to fresh evaluation of the limitations to the development of our own products and processes.

I have tried to look at that old-fashioned equipment, the transformer, in this way, and hope I have shown that in several respects there is still a lot of undeveloped open country ahead of it. You may not agree with my views about this or the other equipments I have touched upon, and although at this moment you may be rather powerless to answer back, I have no doubt that you will speedily find ways of doing so. But I on my part should very much like to hear your expositions in the same vein on your own products, and, of course, in turn to have the opportunity of commenting on them.

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UTILIZATION SECTION: CHAIRMAN'S ADDRESS

By J. M. FERGUSON, B.Sc.(Eng.), Member.

'DEVELOPMENTS IN ELECTRICAL PLANT FOR INDUSTRY'

(ABSTRACT *of Address delivered 13th October*, 1960.)

INTRODUCTION

The standard of living of an industrial country is dependent upon two factors: first the wealth of the natural resources of the country, and secondly the productivity of the workers.

Up to the present it has not been possible to exercise any control on the natural resources of the country, but the dream of the alchemist in his search for transmutation of elements to precious metals has persisted for many centuries. We are just now remotely seeing the possibility of means for controlling and producing the basic material a country requires synthetically, but although this may be possible in a laboratory at the present time, it is quite impossible on any practical scale. At present, the only factor under our control which could be developed to yield increasing returns is the productivity of the worker.

Although this country led the world in the Industrial Revolution, we have now in relation to other countries quite a long way to go. Recent comparisons[1] of outputs in the United States and Great Britain show that the total output per worker in the United States is nearly double that in this country, and in the manufacturing industry the average output per worker in the United States is three times that in this country. In the basic metal industry, for example, the energy required for a unit output is much the same in both countries, so that this is equivalent to saying that the worker in the United States has at his command two to three times the power available in this country. In other than the basic metal industries this ratio may be higher. It is clear that increasing productivity will be coupled with a growing demand for energy.

Achievements of the supply industry have been spectacular and widely appreciated. Principally two factors—first, the great expansion in size of generating units leading to higher efficiency and lower capital cost, and secondly, development of large interconnected high-voltage networks, making possible economic siting of power stations and economy in reserve plant—have resulted in electrical power over the past few years increasing by only 20% as against a much greater increase in the cost of other fuels. This means that, in the increasing demand for energy, its use in electrical form has been particularly stimulated, and it is not surprising that in the utilization field many users are increasingly electrifying plant, as, for example, in the steel, mining and transport industries.

ELECTRIC DRIVES

Types of Motors

Power for industry, apart from energy for electrochemical and electrolytical processes dealt with by our Chairman last year, is supplied in general by rotating machines of which there are three broad categories:

(*a*) Squirrel-cage induction motors.
(*b*) Wound-rotor induction motors, and synchronous salient-pole motors.
(*c*) D.C. motors.

Mr. Ferguson is with the English Electric Co., Ltd.

The choice of an appropriate motor is determined by performance, first cost and running costs. The first cost is evidently affected by speed, rating and duty, but a general comparison of relative costs is shown in Fig. 1.

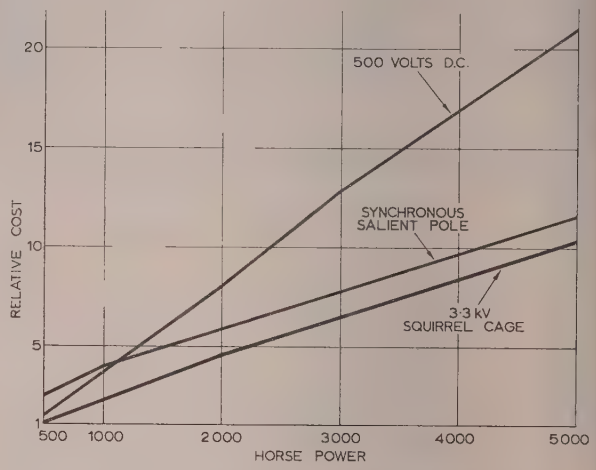


Fig. 1.—Relative costs of motors operating at 1 000 r.p.m.

Constant Speed

Where relatively constant speed is required, first cost, running costs and general robustness all weigh heavily in the direction of squirrel-cage induction motors. Such a requirement arose in the design of the diffusion plant at Capenhurst, where a large number of compressors were required to produce the pressure drop of the uranium hexafluoride gas across the porous membrane for the diffusion process. Large numbers of squirrel-cage motors, amounting to some hundreds of thousands of horsepower, were chosen for this duty.

Where the supply is limited for direct-on-line starting or where power-factor correction is called for, a synchronous wound-rotor machine may be used.

Variable Speed

Variable speed is an essential requirement for a very large number of industrial drives, and by far the greatest proportion of these are still supplied by d.c. motors. In spite of disadvantages, the suitability of such motors to meet high torques, reversing duties, and accurate control, makes them virtually unchallenged in a number of fields such as traction, mill drives, etc.

Initially some form of rotating convertor was used to generate the direct current for such drives, but over the years there has been a steady swing towards the use of mercury-arc convertors, and more recently to silicon and germanium. The use of static convertors is relatively straightforward where there is

o requirement for regeneration, and this has been common ractice for many years.

Packaged variable-speed d.c. drives working direct from the 00-volt a.c. supply are readily available up to 100 h.p. Variable peed is obtained by varying the armature voltage with fixed eld excitation, using a transistor-driven 3-phase magnetic-mplifier circuit. The motor-armature terminal voltage is com-ared with a reference potential produced by the setting of the peed controller. The error is fed to the controller, which djusts the speed of the motor, maintaining speed to within pecified limits independently of the load.

Grid-controlled mercury-arc convertors are now increasingly eing used for reversing drives where regeneration is important, .g. in steel mills and mining,[3] instead of the Ward Leonard or lgner set.

By its nature a rectifier is a unidirectional current-flow device, nd therefore to cater for reverse current flow for regeneration ither duplicate installation must be used connected back to back or a reversing switch must be used in the armature or field circuit of the drive motor to reverse its polarity (see Fig. 2). In

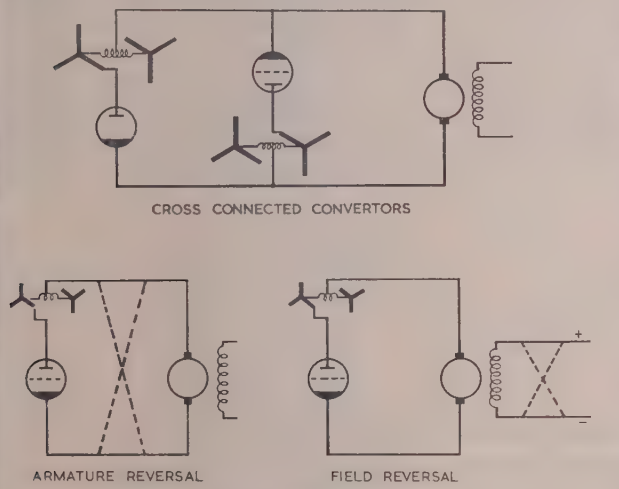


Fig. 2.—Systems used for obtaining reverse current flow with mercury-arc convertors.

practice all three methods have been used, but for economy a single convertor bank with an armature reversal switch or field reversal switch according to the duty is now generally used. This switch must be capable of a very large number of operations, although it is not normally called upon to interrupt current, as the control of the convertor is arranged to reduce the current to zero through the switch before it is opened.

Because of its lower cost, greater robustness and less need of maintenance, a great deal of effort has been directed towards making the a.c. squirrel-cage motor suitable for variable-speed drives, although inherently it is a constant-speed motor for any given supply frequency. If the supply frequency is variable the induction motor will evidently be a variable-speed drive. Generation of variable frequency, however, is normally a costly item and only justified in special circumstances. This scheme has been adopted for the compressor drive[4] to the supersonic wind tunnel at the Royal Aircraft Establishment, Bedford, where the variable frequency is generated by a gas-turbine-driven alternator rated at 30 MW. It has also been used for the carbon-dioxide blower drives for the Hinkley Point atomic power station, where six gas circulators are driven by six 7000 h.p. squirrel-cage induction motors supplied from a variable-speed turbine and alternator set, and a similar arrangement is used for the Bradwell atomic power station.

Any economical method of generating variable frequency would increase the application of squirrel-cage induction motors for variable-speed drives. Controlled semiconductor devices may open up more attractive ways of producing the variable frequency for such drives.

An ingenious method of producing a variable frequency of 0–20 c/s has been devised by the use of grid-controlled mercury-arc convertors or controlled semiconductors, as shown in Fig. 3. The system comprises three grid-controlled rectifier equipments with their outputs connected in delta. If these equipments are all controlled to zero output voltage, no current will flow round the delta. Advancing the grid impulse on all grids equally will cause current to flow around the delta, although the voltage across the output terminals will still be zero, since the d.c. outputs are virtually short-circuited. If the grid impulse is advanced and retarded cyclically so that the output voltages form a 3-phase system, the sum of these voltages will be zero, and the same direct current will flow round the delta. Under these conditions at least one of the equipments must be inverting, and possibly two, while the other is rectifying. The three output terminals of the delta are now providing a 3-phase low-frequency supply determined by the frequency of the grid-impulse movement.

Packaged variable-speed drives using induction motors of low horse-power with speed controlled by series reactors are available. In this scheme the induction motor is supplied from a 3-phase source through the a.c. windings of a transductor, and the d.c. winding is energized from a transistor d.c. amplifier stage (Fig. 4). Variation of this d.c. output causes corresponding variation in the voltage of the a.c. supply to the motor stator winding by the transductor, so that, by controlling the output of the d.c. amplifiers, the motor speed can be controlled. The output of an induction tachogenerator is rectified and compared with a d.c. reference potential representing the desired speed. Any difference between these two voltages is fed as an error signal to the transistor driving stage, which then controls the transductor a.c. output and hence the motor speed. Such control, however, is only suitable for relatively small horse-powers, since the efficiency and power factor fall off markedly as the speed is reduced.

Squirrel-cage induction motors may also be used for variable speed by using a slip coupling to the drive. This can be either a magnetic or mechanical form of coupling, but it inevitably leads to some loss of efficiency at the reduced speeds. Active research and development has been devoted to other means of making squirrel-cage a.c. induction motors suitable for variable speed, and these are described in the following Section.

For many years induction motors with wound rotors have been used for variable speed by controlling the resistance inserted in the rotor. Such induction motors can also be used to reduce the starting shock on the system, by suitable control of the rotor resistance, but the great advantage of a squirrel-cage machine, i.e. no brushes, slips rings or commutator, is lost.

MOTOR DEVELOPMENTS

Induction Motors

New requirements for induction motors have fallen well within previously accepted design limits and have not called for any new techniques. However, the rating for special duties such as boiler feed pumps has kept pace with the increasing size of turbo-alternators—a 60 MV set requiring a 1400 h.p. motor, and a 200 MW set a 6000 h.p. one. Direct boiler pump drive at 3000 r.p.m. has been chosen as the most suitable speed for these

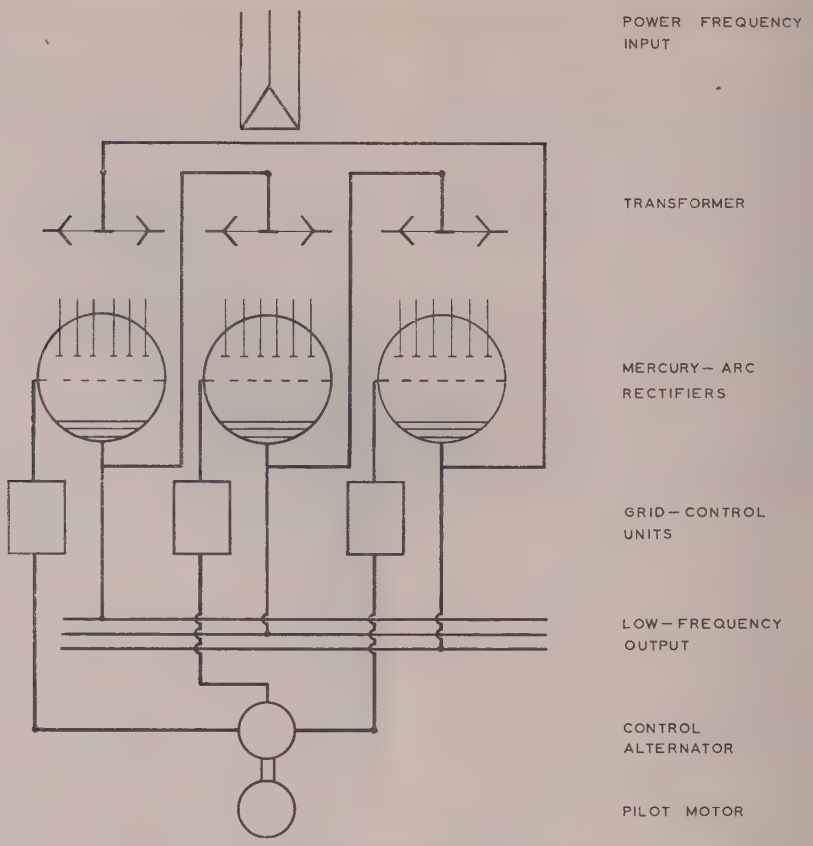


Fig. 3.—Simplified diagram of frequency convertor.

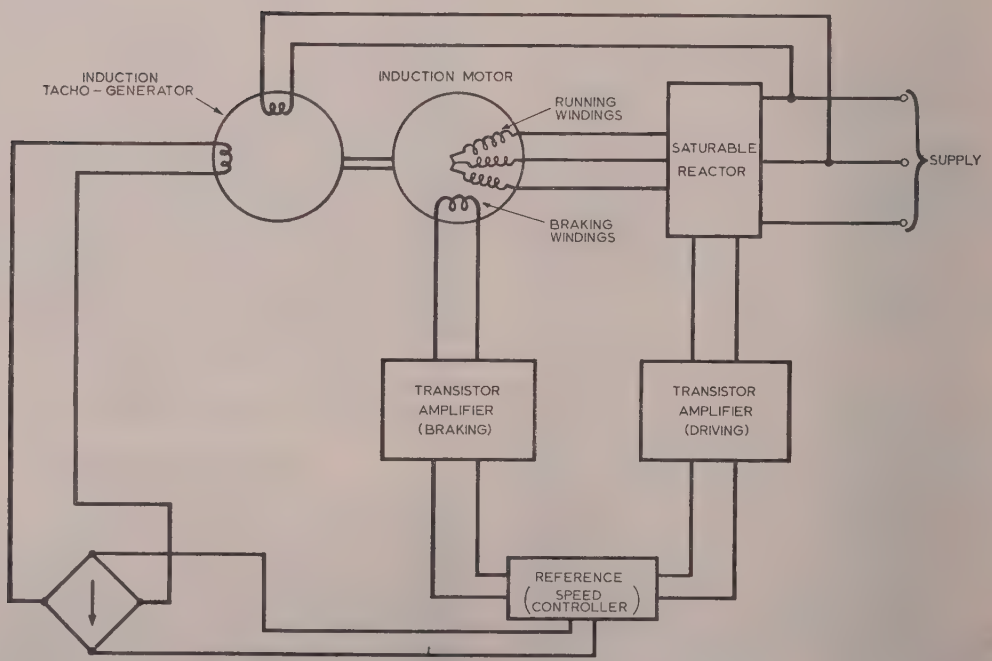


Fig. 4.—Block diagram of ¼ h.p. a.c. motor speed controller.

motors, and this has called for a sturdy design to give very high efficiencies of the order of 97%. For larger alternator sets there is a tendency to raise the speed of the boiler feed pump, thus necessitating the introduction of gears, and lower speeds may be adopted for the motor drives.

The trend to semi-outdoor stations has led to the requirement of naturally ventilated machines suitable for outdoor operation. The end-windings have been insulated with silicone rubber as a protection against moisture. A top-mounted baffle chamber is used with suitable baffling to prevent the ingress of dirt. Silicone elastomer is likely to be more widely used even with standard open protected motors as it becomes less expensive; and this will certainly be more economic than closed air-circuit motors.

Reference has already been made to the considerable efforts directed towards achieving variable speed directly from a type of squirrel-cage induction motor. Pole changing[6] has been developed as one solution to this problem. This gives definite speed ratios suitable for fan drives, etc., where the selected speed does not require continuous variation.

A similar result can be achieved with a type of induction motor having the stator wound with a composite coil, equally pitched and insulated, to give two windings of, say, 8 and 10 poles for two speeds.

Various forms of squirrel-cage induction motor have been described which can be arranged to give variable speed, e.g. the spherical induction motor,[7] the logmotor and the method of using phase-shift control on the stator windings, but at present these are under development and not yet in significant operation.

subject will be read and discussed during the forthcoming session. Notwithstanding this effort the commutator of a d.c. machine remains one of the most highly stressed and difficult parts of the machine to design.

To meet the demand for larger outputs from d.c. machines, significant use has been made of various types of duplex windings. This type of design enables the voltage between adjacent commutator bars to be reduced, compared with a conventional single-lap winding, and this helps commutation and reduces the risk of flashover. These advantages have been confirmed in service operation, but, in general, duplex windings appear more sensitive to a change in commutation conditions, which can upset the current balance in the windings to give rise to deterioration. Long-term stability of duplex windings to give satisfactory commutation appears more difficult to achieve than in the single-lap design.

Conventionally d.c. machines have been built with solid-rolled-steel or cast frames, with laminated main poles and compoles. Changing flux conditions induce eddy currents in the solid frame which slow down the response of the main and compole flux relative to their respective currents. Modern control schemes have increased the current changes in machines to high values, and this lag between current and flux adversely affects commutation. In some cases it is practically impossible fully to compensate for this effect in the design of the control circuits.

Laminated frames as well as laminated poles have therefore been introduced to meet these transient conditions. Fig. 5 illustrates the difference in performance of a solid frame compared with a laminated frame for a 1·6 MW 500-volt machine with a peak current of 9·6 kA.

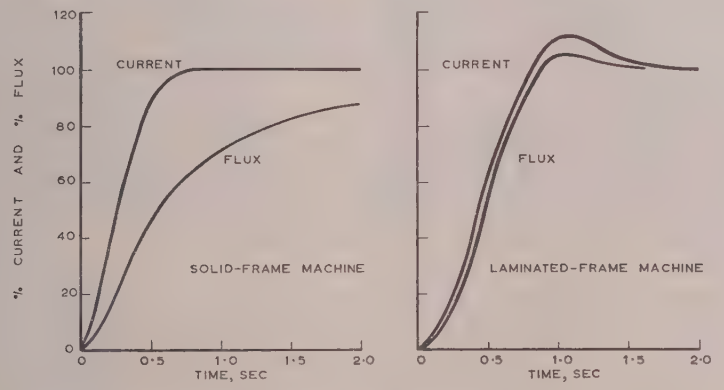


Fig. 5.—Comparison of solid-frame and laminated-frame d.c. machines.

Wound-Rotor Motors

In large-horse-power motors there are control problems of starting, and cooling the rotor winding, particularly the end-winding regions, during this period is difficult. The technique of using hollow conductors, developed for large turbo-alternators, has been used to solve this problem and a motor for 6 200 h.p. 3 000 r.p.m., has been built; this machine has closed air-circuit and water-cooled heat exchangers.

D.C. Motors

For variable-speed drives the d.c. motor has been largely unchallenged over half a century. Despite this, there have been no startling new developments but rather a steady evolution in design. Throughout, commutation has been one of the most difficult problems and is still not adequately understood. Much research and development is directed towards this at present, and considerable progress has been made with the aid of digital and analogue computers to a better understanding analytically of this phenomenon. It is probable that some papers on this

In addition to technical details involving design, a great deal of consideration has been directed towards making d.c. machines less sensitive to dirt and moisture from their surroundings, and to increasing the reliability of operation under all conditions.

CONTROL

Industrial equipment in the initial stages of use is subject to direct manual control. This is the case in traction, mining and steel rolling mills, where an operator has traditionally been directly responsible for controlling the amount of power used at any time in his drive, and therefore directly controlling the speed and acceleration of the drive. With the steady demand for increased output from a given plant requiring consequent speeding up, the responsibility of the driver has been increasingly taken over by the control scheme. Under one type of supervisory control the driver can select a desired speed, and acceleration to this speed may be controlled to an optimum value, subject

to the safety of the plant, by the control scheme. Once a desired speed is achieved or selected, it can be held to a constant value within almost any practical limits by suitable closed-loop controls and adequate feedback information.

This control can be applied to a number of drives operating in series on a manufactured product, and the necessary relative speeds can be obtained with accuracy, thus leading to acceleration of processes such as paper making and multi-stand rolling mills.

Analogue computers are now available and in regular use for the study and simulation of such control systems, in order to ensure adequate stability under operating conditions. For such studies d.c. machines are much more suitable, because of their linear characteristics, than sub-synchronous a.c. machines.

In any control problem involving high-power drives one of the most important units is an adequate and suitable amplifier. Electronic amplifiers, rotating amplifiers, and more recently magnetic amplifiers, have all been used with success. Reliability is a most important requirement for control gear associated with expensive capital plant, and for this reason perhaps the greatest contribution to the control field was the introduction of the magnetic amplifier, because this depends upon conventional materials well understood by the normal maintenance engineer and does not require either a vacuum or mechanical movement of parts. Many years of experience have now been achieved to prove that plant can be operated more consistently and reliably to higher speeds under the control of automatic control gear than is possible under direct manual control from the operator. It is of interest that controlled semiconductor rectifiers, capable of handling very significant powers, and transistors may provide further developments in amplifiers for this type of control gear as an alternative to the magnetic amplifier, but still with adequate reliability.

This experience of manual supervisory automatic operation of plant has been essential to pave the way for ultimate complete automatic operation. With experience of the reliable automatic control of separate motions of complicated plant, it is now possible to co-ordinate a number of these operations in sequence and completely control complex equipment in accordance with a prepared programme contained in a punched card, tape or other sources of stored information.

Parallel development of high-speed computers has also now reached the stage where serious consideration may be given to control of equipment not only from stored programme, but from up-to-date information and data which can be processed at high speed and used to modify or optimize the process in a time that could not be achieved by a human operator.

Before this is widely applied to the direct control of large industrial plant we require knowledge of the reliability such a system will give and to be quite certain that in each case the increased complexity will bring a certain and adequate reward.

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CENTRE, SUB-CENTRE AND GROUP CHAIRMEN'S ADDRESSES

The Institution of Electrical Engineers
Abstract No. 3492
Jan. 1961

MERSEY AND NORTH WALES CENTRE: CHAIRMAN'S ADDRESS

By DONALD A. PICKEN, Member.

'THE EFFECTS OF ELECTRICITY ON HUMAN BEINGS'

(ABSTRACT *of Address delivered at* LIVERPOOL *3rd October*, 1960.)

To understand the effects of electricity on human beings it is esirable to know something about the parts of the body which ıay be affected.

The skeleton consists of a hinged structure controlled by a ıuscular system which operates entirely by contraction whether or expanding the chest or gripping a tool. The muscles themelves are, for our purpose, of two types: the striated muscle, vhich is controlled by the central nervous system; and the artially striated muscle, which has inbuilt nervous features and an therefore operate in isolation from the central nervous ystem. The muscular system contracts on the application of ulses of current at a frequency of about 100 per second. The igher the peak value of the pulse the more powerful the ontraction.

The nervous system consists of a network of what literally are onductors and serves to carry information and instructions from ensors to the brain and thence to the operating muscles or in he case of the partly striated muscle directly.

The brain consists of discreet centres all operating on an lectrochemical basis. Memory is stored probably by an laborate system of voltaic cells which operate like the electronic rain, except that in addition to operating in two states, charged r uncharged, they can also operate by degrees of charge. Memory also serves as the origin of the nervous pulses which ontrol most parts of the body.

The lungs consist essentially of air sacs in which air is brought nto very close proximity to blood, with only a thin permeable nembrane between and through which oxygen can pass from he air to the blood and carbon dioxide can be eliminated from he blood. These air sacs are contained within the thorax, which s enclosed by the thoracic wall under the ribs and by the diaphragm. Contraction of these muscles increases the volume of he thorax and this induces air into the lungs; relaxation of the nuscles causes air to be expelled.

The blood circulatory system is operated by the heart, of which he right-hand system pumps blood through the lungs, where he products of oxidation of body tissues, principally carbon lioxide, are eliminated and oxygen is absorbed into the blood, vhich is then circulated by the left ventricle via the arteries and he capillaries of the muscles, skin, etc., where oxygen is supplied o enable energy to be developed and the products of the reaction liminated. The blood then returns via the venous system to he right auricle, and thence from the right ventricle to the lungs, vhence it returns via the left auricle to the left ventricle. The ieart can be controlled by the central nervous system—the ncreased rate of beating caused by fear is an example—but a ieart separated from the body will continue to beat so long as ources of energy are provided and products of reaction removed.

Normal 50c/s alternating current can be thought of as 100 pulses per second, as the nervous system operates on a pulse irrespective of its polarity. The application of 50c/s alternating current to muscles will therefore affect them just as do the hundred pulses per second of the nervous system.

If electrodes are applied to the hand and forearm so that current passes through the wrist, effects can be studied without risk to life; a current through the wrist of 0·5–2mA will cause a slight sensation and a current of 3–6mA will affect the nervous system in such a way that pain in the region of the wrist, such as that caused by pulling out a hair or prodding with a needle, will not be felt.

If the current is increased greater difficulty will be experienced in operating the muscles, and at 8–20mA the muscles will become immobile by complete contraction and it will not be possible to release the grip of the hand. The sensory nerves will still be insensitive, and pain apart from heat due to the resistance at the points of entry and exit will be slight. If a current of 20mA or more were suddenly applied the contraction could be such as to crush bones or tear muscles.

If, instead of through the wrist, current is passed, say, from hand to foot at about 20–50mA, the muscles of the thorax will be forced into contraction, the lungs will be abnormally filled with air and will remain so as long as current flows, and as no exhalation can take place, waste products will build up in the blood; in a few minutes irreversible changes will take place in the brain which will prove fatal. On cessation of the current the patient may not recommence breathing, owing to muscular fatigue, non-elimination of combustion products or effects of current on nerve ends. These effects are normally reversible, and artificial respiration will be effective if promptly applied and maintained.

If the hand-to-foot current is of the order of 50–500mA the current density through the heart will be of the same order as that through the wrist which affects the nervous system of the wrist, and instead of the heart beating in a co-ordinated manner the individual fibrils will contact haphazardly; the resulting phenomenon, known as 'fibrillation', will almost entirely stop blood circulation. Even short-time passages of current (0·1sec) can have this effect if they occur during the sensitive phase of the heat beat, and all periods of current flow exceeding one heart cycle (about 1sec) must include such a phase and will produce fibrillation; for when the heart fibrillates it does not normally resume the sensitive phase so that co-ordinated beating is not resumed even when current ceases. Unless effective steps are promptly taken the brain will suffer such changes that death is inevitable.

To restore heart action, either a severe shock must be given to the heart to produce tetany of the muscles or chemical methods of stopping the fibrillation such as injection of acetylcholin must be adopted. There is doubt as to whether fibrillation can be eliminated spontaneously, but this in any case is only of academic

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interest unless oxygenated blood circulation to the brain can be restored within 3–5 min.

If a current of the order of amperes flows, there will be the contraction of the thorax and the current through the heart will be such as to cause the heart muscles to contract, but when the current ceases, provided it has not been too prolonged, the heart is likely to resume beating either spontaneously or as a result of movement such as results from a blow on the chest or the action of normal artificial respiratory techniques. Thus higher currents are less likely to produce immediate death than currents under one ampere, and indeed currents of the order of amperes may cause fibrillation to cease, and were it not for other effects would be a useful method for lay treatment of fibrillation. Such currents, however, as well as giving serious risk of burning may also have effects on the nervous system which render it incapable of controlling the muscular system. The risks of these effects is such that lay application of these countershock treatments for fibrillation is dubious, particularly as the diagnosis of fibrillation is difficult for a doctor without electrocardio apparatus.

Wherever such currents flow there will be internal heating effects which may be very serious, and whilst unlikely to cause instant death, may well do so after a few days unless steps are taken to eliminate the myoglobin which may result from the injuries. The drinking of alkaline liquids such as one dessert-spoonful of sodium bicarbonate in a tumbler of water is very beneficial for such a purpose.

The resistance of the body has two components, both variable. One of these is skin resistance, which may vary from 10^4 ohms/cm^2 to 10 ohms/cm^2, depending chiefly on the humidity of the skin. This factor is influenced by perspiration, which can result from the passage of a small current through the skin, so that, whatever the initial dryness may be, with a 240-volt supply the current flow will be such that, unless the contact can be broken immediately, perspiration will ensue and the current will increase and set up an effect which will rapidly reduce the skin resistance to a negligible value.

The second effect is the internal resistance of the body, which is of the order of 200–800 ohms and varies inversely with the applied voltage.

The overall resistance varies inversely as the 1·5–1·9 power of the voltage. Thus reducing the voltage from 240 to 110 will increase the effective resistance by about 4 times and decrease the current by about 8 times.

This is borne out by a statistical survey carried out by W. H. O. de Bats, Senior Electrical Inspector for Holland, who found that after eliminating factors not common to both systems the 220-volt system was 6·5 times as likely to produce electric-shock accidents as an 119-volt system.

Voltages of the order of 20–60 volts a.c. are likely, given effective contacts, to result in inability to let go if one of the contacts is gripped as an electric tool would be.

Similarly a voltage of 40–100 volts across a path which traverses the chest will stop the breathing, and 80–600 volts is likely to result in fibrillation. Over this range of voltage, nerve blocks and burns are the most probable effects, but if the contacts are poor, for example through somewhat insulatory floors or footwear, the voltage across the body may be 80–600 volts with much higher system voltages.

Capacitor and lightning discharges normally are too short to affect the nervous system, but serious burns can result, though they are often merely superficial.

In a recent case the discharge of a 114 μF capacitor, charged at 4 kV, across a man's chest had no effect apart from severe burns and nervous shock, and the injured man was able to walk to the ambulance room for treatment.

Frequency has little effect at any practicable supply value, though increasing the frequency by 10 times may increase the safe values by 20%, i.e. a typical let-go current would be 15 mA. At 10 kc/s the let-go current is about 80 mA, and above about 15 kc/s there is little effect on the muscular system, though heating effects are unchanged.

Direct current only affects the muscular system with the onset and cessation of the flow; these can cause a violent jerk, and the sensation resulting when contact is broken no doubt accounts for the impression that 'd.c. throws you off'. Small direct currents up to 0·1 amp are negligible unless protracted, but higher current and small currents for a longer period, in addition to causing serious burns, can give rise to electrolytic effects which may seriously affect the nervous system.

The effect of ambient temperature as a factor in electric shock is shown by the following table, which gives a twenty-year (1928–48) month-by-month list of accidents which have occurred in Switzerland. It was prepared by the Power System Inspection Service of the Association Suisse des Electriciens:

January	137
February	131
March	182
April	138
May	218
June	305
July	301
August	262
September	219
October	212
November	163
December	141

It will be noted that the incidence rate increases broadly as the temperature increases and subsequently decreases again. Bearing in mind that the hottest months are also the holiday months when the incidence is likely to fall, these figures are quite striking. Less elaborately based figures for ten years in a section of England show a similar tendency:

January	48
February	35
March	55
April	60
May	62
June	60
July	56
August	67
September	63
October	60
November	66
December	45

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NORTH-WESTERN CENTRE: CHAIRMAN'S ADDRESS

By F. LINLEY, Member.

'ACHIEVING OUR PURPOSE'

(ABSTRACT *of Address delivered at* MANCHESTER *4th October*, 1960.)

The 1947 Electricity Act presented an opportunity, which was unprecedented and unrepeatable, to reshape electricity supply both administratively and technically on the broadest possible front.

The Address is an examination of the evolutionary processes and resultant pattern in Greater Manchester, which is the No.1 Sub-Area of the North Western Electricity Board.

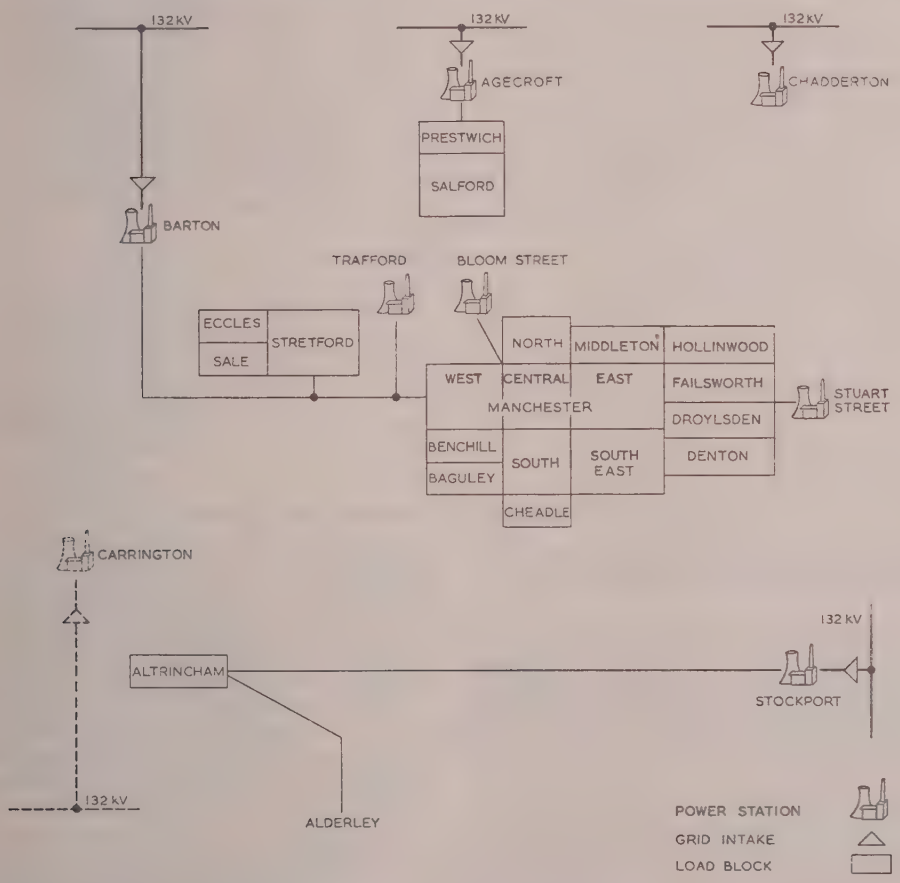


Fig. 1.—Supply arrangement: before nationalization.

Creating the Districts

This Sub-Area is geographically almost the smallest in the country, and yet contains the greatest concentration of commerce and industry. The electricity supply was formerly provided by seven separate undertakings, and the overall result was neither efficient nor economic.

For administrative purposes the Sub-Area is divided into Districts, and selection of their sizes and boundaries offered many choices and problems. The engineering aspect took precedence, and the decision was taken to ignore completely both municipal and undertaking boundaries.

From examination of the practices of former undertakings, it appeared that a consumer content of about 60 000 was the figure at which the staffing pattern tended to change towards that of centralized specialist groups, and this figure was taken as a broad basis in determining District size. As few easily definable centres of population existed, easily recognizable physical or geographical features such as the Manchester Ship Canal, the Rivers Mersey and Irwell and the main railway routes were selected as District boundaries. Subsequent experience has shown that over 80 000 consumers and their associated system can be handled satisfactorily as a District. Specialist functions were concentrated on Sub-Area headquarters, whilst all local engineering matters were decentralized to Districts.

The great amount of rapid redeployment of staff which took place made it necessary to appoint executive officers to maintain liaison between the ex-undertakings and the Board until com-

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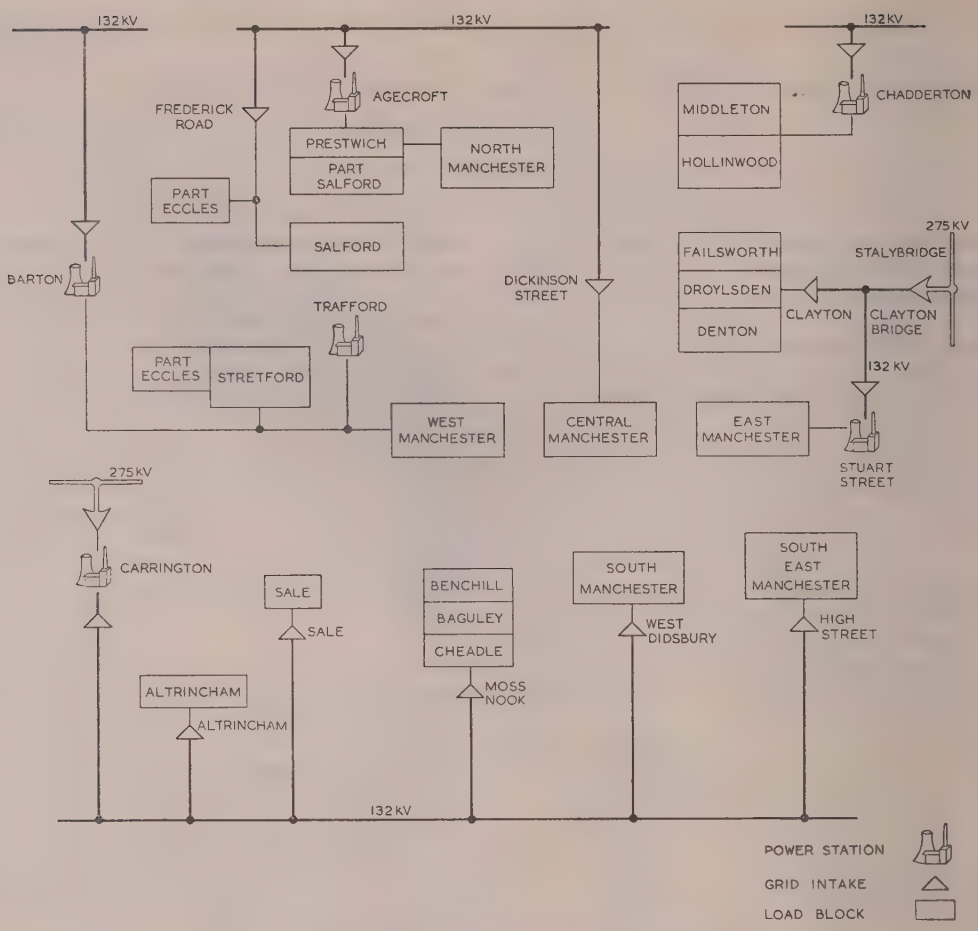


Fig. 2.—Supply arrangement: 20 years after nationalization.

plete reorganization had taken place. Within six months of nationalization the first District was in independent operation.

Pooling the Sources of Power

On nationalization, the existing power supply development schemes were discarded, and the Address gives details of the actions taken jointly with the Central Electricity Generating Board to sectionalize the system and create new Grid intakes under completely new schemes.

Fig. 1 shows the position at the time of nationalization. The most outstanding feature was that 340 MVA, i.e. 84% of the total load, was all carried on one 33 kV solidly interconnected system with only one Grid connection. The addition of more intake points has greatly improved security and stability. The outdated switchgear at Barton has been replaced, all 33 kV system protection has been modernized, and 80 interchanges of 33 kV circuits have been made to make the greatest possible use of existing cables.

The growth of load by nearly 6% per annum compound has taken it from the initial 400 MVA to over 700 MVA, and this may well be 1 100 MVA in 1968. The planned supply arrangement, 20 years after nationalization, is shown in Fig. 2.

11 and 6·6 kV Systems

The problems in the lower voltage ranges were quite different and the most urgent one existed in the Altrincham distribution system, where there was the utmost difficulty in maintaining supplies. This consisted of extensive 2 kV single- and 2-phase networks reinforced by the nucleus of a new 11 kV system. The greatly overloaded 2 kV networks supplied single-phase transformers designed for 83·3 c/s working, standing in consumers' premises or in small undrained pits in pavements.

The development of the 11 kV system has now been carried out, 41 new standard 11 kV/415-volt substations have been constructed, and the 2 kV system has been largely replaced by a modern 3-phase 4-wire network. The final stage of replacing the small-section secondary twin distributors and service cables is now in hand.

The improvement in reliability is indicated by the fact that in 1948 when the load was 13 MVA the number of consumer hours lost due to faults was 36 000, whereas in the first eight months of 1960, when the load was 30 MVA, it was only 120 consumer hours. Over £500 000 has been spent to date on the 11 kV and lower-voltage systems at Altrincham.

To assist in meeting the rapidly rising load in the south of the Sub-Area, a considerable part of the ex-Manchester 6·6 kV system has been uprated to 11 kV working. This step was accompanied by a disturbing number of faults, but the decision has paid and uprating may continue on a considerable scale.

It is estimated that by 1968 the number of substations in commission will be approximately 2 000, necessitating a steady commissioning rate of one every three working days. The difficulties of obtaining sites in these numbers in an urban area

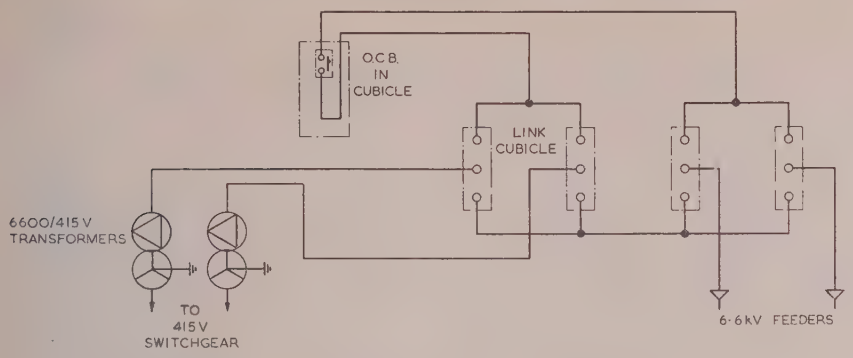


Fig. 3.—'Manchester'-type 6·6 kV substation.

re most acute, and recourse is being had on an increasing scale o transformers in underground chambers or buried in footpaths.

Replacement of switchgear of inadequate breaking capacity is ow approximately two-thirds complete, at a cost of £200 000. he amount of replacement possible by standard arrangements f single-bus metalclad units has been surprisingly small, largely wing to the existence in the ex-Manchester system of the nusual substation arrangement shown in Fig. 3. Here the ngle oil circuit-breaker can be made to control any of the four rcuits at will.

This arrangement of 2-way link cubicles with a cable busbar as been widely used in large substations in conjunction with uplicate busbar switchboards, so creating a 3-busbar arrangeent. This complex but flexible system enables very efficient istribution of loads between feeders and transformers to be ade, provides standby with a minimum number of cables, and ives a very high plant utilization factor. It has had to be etained in the replacement scheme to maintain system capacity.

Controlling the System

The continuously manned control centre on the ex-Manchester ystem was made the point of authority for all high-voltage witching operations. All co-operation with the C.E.G.B. on witching matters, and with the twelve industrial firms who run total of 80 MVA of private generating plant in parallel with ne Board's system, is carried out through this centre.

Facilities for control or alarm have been expanded to include 55 substations, and the centre co-ordinates the switching of 350 network stations. This remote supervisory control equipent was of great use in the days of load shedding.

A top priority task was the early production of a standard ystem of operational diagrams, with standard nomenclature nd safety rules.

The communication system was developed, extensions being ade to the private telephone network, and mobile radiolephone coverage given to the whole of the Sub-Area.

The newly created specialist sub-sections were given the job f development of standard techniques for constructional and perational work. Major economies and advantages have since esulted in such fields as substation design, meter testing and epair, mains records, and cable laying and jointing techniques. n example is the introduction of fault location on h.v. cables y a high-voltage discharge method, which enables the position f a fault to be determined within inches on feeders many miles ng. This development has enabled a 33 kV feeder to be repaired within twenty-four hours, as against a week which would have been considered fast not many years ago.

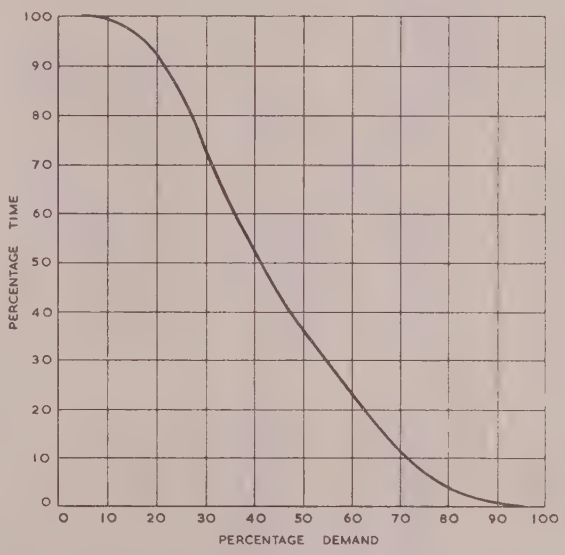


Fig. 4.—North Western Electricity Board, No. 1 (Manchester) Sub-Area: duration/load curve for 1958.

Experience showed that to impose standard techniques on the wide variety of systems and plants existing, and to do this through the agency of people who were equally varied in experience and opinions, needed great effort.

Conclusion

The Address concludes with an examination of the use made of the plant installed as a result of these efforts. Fig. 4 shows the time a unit of load is present on the system, and the conclusion was drawn that such inefficient use of the nation's man-power and resources indicates the need for fuel cells or energy storage to meet local peak demands.

The work in the past years can be considered in two parts: meeting the growing demands of nearly half a million consumers at a rate which they dictated, and creating a new single organization from seven separate ones. This stage of dual effort is now past, but the magnitude of developments in the clearly foreseeable future indicates no reduction in effort.

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SCOTTISH CENTRE: CHAIRMAN'S ADDRESS

By R. B. ANDERSON, M.I.Mech.E., Member.

'THE DEVELOPMENT OF ELECTRICITY SUPPLIES IN THE NORTH OF SCOTLAND'

(ABSTRACT *of Address delivered at* EDINBURGH *4th October, and* GLASGOW *5th October*, 1960.)

So far as I have been able to ascertain, the first public supply of electricity in Scotland was given from a small hydro-plant at Fort Augustus in Inverness-shire, where an 18 kW water turbine and an oil engine of similar capacity were installed to supply Fort Augustus Abbey and the village of Fort Augustus, with its population of 800. A non-statutory undertaking was established in 1890, and continued to supply the village until 1951, when the North of Scotland Hydro-Electric Board took over the responsibilities and replaced the overhead network.

The first public supply in Great Britain was given in 1881, and the first power station seems to have been at Godalming, in Surrey, where the waters of the River Wey were used to drive a water turbine. It was enterprising but unsuccessful, and closed down three years later, the street lighting going back to gas. A steam station constructed by Edison's engineers at 57 Holborn Viaduct, London, in 1882, was, however, the first station to provide a public supply for purposes other than arc lighting.

All the essential technical inventions and discoveries had certainly been made many years before 1890. Nevertheless, it seems quite remarkable that the monks of St. Benedict's Abbey in remote Fort Augustus were so well informed that, within eight years of the first experimental station being established in London, they were able to bring into operation their own plant and distribution system.

In this Address I refer to the progressive development which has taken place resulting in electricity supplies being provided throughout the territory now forming the District of the North of Scotland Hydro-Electric Board, that is, the area to the north of the Firths of Clyde and Tay, comprising some 22 000 sq miles and making up three-quarters of the land area of Scotland and one-quarter of the land area of Great Britain. It has a population of about 1 200 000, which is a quarter of Scotland's population and about 2½% of that of Great Britain.

The main developments in the North of Scotland during 45 years from 1890 are shown in Table 1 in the order in which they took place. According to this, there were 12 municipal undertakings covering a population of 453 000 and 26 company undertakings with a population of 178 000. It is, I think, quite a creditable record and shows that, although many of the developments were small, the initiative was there and some of the population, at least, were ready to take advantage of the new amenity.

1922–1948

What I have selected as the second phase of electrical development in the North of Scotland commenced with the advent of large-scale hydro-electric development for public supply.

The Water Power Resources Committee, appointed by the Board of Trade and under the Chairmanship of Sir John Snell, reported to the Government in 1919 on the steps which should be taken to ensure that the water resources of the country were properly conserved and systematically utilized, and recommendations were made concerning the use of water in the Scottish Highlands as a source of power for the generation of electricity.

Shortly after this—in 1922—the Grampian Electricity Supply Bill received the approval of Parliament. The Act authorized the impounding of water power resources, particularly in the Highlands of Perthshire, and included Lochs Ericht, Rannoch and Tummel, and also provided for transmission and distribution lines throughout the Counties of Perth, Kinross and Angus, and parts of Inverness-shire, Argyllshire and Stirlingshire.

Construction work at Rannoch commenced in 1928 and was completed in November, 1930. The station was equipped with two sets totalling 43 000 kW, and took over supply for the major part of the Grampian load.

The Tummel power station development commenced in the spring of 1931 and was brought into operation in November, 1933, adding a further 36 000 kW to bring the total hydro-electric plant capacity in the valley to 79 000 kW.

A 132 kV steel tower line was constructed from Rannoch, via Tummel, to Abernethy, and when this was brought into operation in 1930 it was claimed to be the first line of that voltage to be erected in the United Kingdom. The line was—and still is—noteworthy. The first 14½ miles between Rannoch and Tummel consist of steel towers averaging 97 ft in height carrying four separate circuits—two for 132 kV and two for 33 kV. With the object of avoiding inductive interference, all conductors are transposed.

A power-line carrier-current communication circuit was provided on the 132 kV lines between Rannoch and Abernethy, and in 1930 this was the first system of its kind in the British Isles. In 1933, after Tummel came into operation, the carrier channel was, in addition, utilized between Tummel and Abernethy for load readings, oil circuit-breaker indications and supervisory control of the Abernethy 33 kV switchgear, and this again was an innovation in this country so far as power-line carrier was concerned.

In 1937, following the Grampian Company's 1932 Scottish Highlands Order, a further somewhat unusual transmission circuit was constructed between Tummel and Keith, near Elgin—unusual because it carried a 132 kV circuit on one side and on shorter arms a 33 kV circuit on the other side. The line was nearly 100 miles long and laid claim to fame by being the longest 132 kV section in the British Isles. The 33 kV circuit was commissioned in 1937, and the 132 kV circuit in July, 1939.

The position by 1938—ten years after construction commenced at Rannoch—was that there had been two important additions to the Grampian Company's authorized idea of supply, with another addition to follow in 1940. With the exception of Aberdeen, Dundee and Perth, the Company had consolidated, on a single network throughout their enlarged area, all supplies previously dealt with by the isolated communities and had gone a considerable way in the establishment of supplies in the country districts.

Aberdeen Corporation during this time continued to generate by steam and had installed capacity of 54 500 kW to meet a system maximum load of nearly 30 000 kW from about 42 000 consumers.

The Carolina Port station of Dundee Corporation had become a selected station, was connected to the C.E.B. system in 1931, and had continued steam generation. The installed capacity

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Table 1

THE DEVELOPMENT OF ELECTRICITY SUPPLIES IN THE NORTH OF SCOTLAND

Supply commenced	Undertaking		Population	Generation
1890	Fort Augustus		800	Hydro/oil
1893	Dundee	Municipal	177000	Steam
1894	Aberdeen	Municipal	180000	Steam
1896	Fort William Electric Light Company Ltd.		3000	Hydro
1898	Rothesay	Municipal	10000	—
1901	Perth	Municipal	35982	Steam
1901 Brechin	North of Scotland Electric Light and Power company (1904)		7246	Steam
1901 Montrose	(Registered in 1898 as Angus Electric Light and Power Company)		10760	Steam
1905 Inverness			28115	Steam
1903	Strathpeffer		5244	Hydro
1903	Oban	Municipal	6567	Steam/oil
1904	Fochabers		—	Hydro
1908	Arbroath Electric Light and Power Company		19503	Steam
1910	Blair Atholl		1580	Hydro
1912	Beauly Electricity Supply Company Ltd.		900	Oil/s. gas
1912	Brora		850	Steam
1914	Lossiemouth and Branderburgh Corporation	Municipal	4500	Suction gas
1914 Ballater	Duncan Electricity Supply Company		1542	Suction gas
1915 Ellon	(Agreement with Town Council)		1261	Suction gas
1914 Kintore			741	Hydro/oil
1920	Alness		500	Oil
1920	Evanton		350	Hydro
1922	Elgin Electricity Supply Company		8810	Oil
1922	Grampian Electricity Supply Company		—	—
1923	Crieff Electricity Supply Company		5544	—
1923	Invergordon	Municipal	1100	Oil
1924	Rothesay	Municipal	10000	Oil
1924	Orkney–Kirkwall Electricity Supply	Municipal	3500	Oil
1925	Dunblane and District Electricity Supply Company		3192	Oil
1926	Kingussie		2393	Oil
1926	Lairg Electricity Supply Company		1000	Oil
1926	Ross-shire Electricity Supply Company		22500	Hydro
1928	Wick Corporation Electricity Supply Company	Municipal	9919	—
1929	Peterhead Electricity Supply Company		12545	Oil
1929	Ullapool (Caledonian Hotel)		180	Oil
1930	Dunoon and District		13050	Oil
1931	Buckie Corporation Electricity Supply	Municipal	8689	Oil
1932	Stornoway Electricity Supply Company		5000	Oil
1932	Lerwick	Municipal	5838	Oil
1934	Thurso and District Electricity Supply Company		3203	Oil
1935	Campbeltown and Mid Argyll Electricity Supply Company		17907	Oil

vas approximately 70000 kW; the city demand amounted to 4000 kW and 30000 consumers were connected.

The year 1939 brought the start of the war and, apart from a urther Grampian Order of 1940, which resulted in a 33 kV ircuit being erected between Rannoch and Oban, and a bulk upply being given to the town, the foregoing was the general attern which prevailed throughout the war years.

Between 1929 and 1941, six Scottish Hydro-Electric Bills ailed to receive Parliamentary sanction. Four of these con-erned Glen Garry and Glen Morrison, and two concerned .och Affric.

The Cooper Committee, which was set up to look into the vhole business of hydro-generation in Scotland, presented its Report in December, 1942. They were of the opinion that evelopment of Scotland's water power resources was in the ational interest and should be used to supplement steam eneration. They recommendations were made effective by the assing of the Hydro-Electric Development (Scotland) Act, 1943.

Between 1944 and 1947, twelve hydro-electric construction chemes were approved by Parliament, involving 16 generating tations with a total capacity of about 440000 kW, and in the ame period 19 distribution schemes covering 4000 sq miles of olated rural area of the West Highlands were submitted to the lectricity Commissioners for approval.

Contracts were placed for 320 miles of 132 kV transmission lines to interconnect the various generation projects and initiate what was to become the Highland Grid.

By the end of 1947, the Board had placed on order 38 hydro-turbo-alternators, varying in individual capacity from 200 to 40000 kW, with a total capacity of 487650 kW. In addition, 82 Diesel generating sets with a total capacity of 23000 kW had been ordered or installed to supply the distribution schemes in remote areas and to extend existing stations and provide power for constructional purposes.

On the 21st December, 1948, the North of Scotland Board's first two hydro-electric stations officially came into commission—one at Morar in Inverness-shire and the other at Lochalsh in Ross-shire.

1948–1960

The well-known Electricity Act, 1947, brought about nationalization. In consequence, the North of Scotland Board took over sixteen local authority and company undertakings with a total of 188424 consumers and power stations with a total capacity of 230000 kW.

The number of people in the district without supply, however, amounted to approximately 600000, or nearly half the population, the majority living in the most sparsely populated areas.

At the end of 1947, the capital expended by the Board had amounted to £7·869 million, and according to the report issued

by the Board at the end of 1959—16 years after they were formed and 11 years after nationalization—the total capital expenditure amounted to no less than £205·288 million.

During this period, 195 818 new consumers were added to the 188 424 connected by the previous undertakings.

The possibility of relatively high average connection costs gave rise to certain doubts expressed in the Cooper Report. This difficulty was early realized and has become progressively more apparent.

In 1948, the average cost of connection was of the order of £100 per consumer: ten years later it had gone up to £270.

Generation

The investment of over £141 million in hydro-generation has been spread over some 38 schemes with a total plant capacity amounting to about 785 000 kW and providing an estimated annual output of 2 148 million kWh. Approximately two-thirds of this output is absorbed in the Board's own distribution areas by their own consumers, and the remainder is sold in bulk, as envisaged in the Cooper Report.

It has not been possible in this Address to describe the technical developments which have taken place. For example, in contradistinction to other Boards in the country, the North of Scotland Board have made extensive use of power-line carrier for protection, control and communication over their entire 132 kV network, and the difficulties of rented Post Office lines and long pilot wires have largely been avoided. Superior forms of high-speed protection have become possible, and the communication and control facilities available at the central control room at Pitlochry are, in many respects, unique. At some group control centres, such as Lochay power station, Killin, carrier is employed for remote control of unattended hydro-power stations.

Fish Research

Considerable research has been carried out in connection with the preservation and development of salmon life. Electric fish screens and electronic counters have been successfully developed and are in regular use.

Future Developments

Probably the most notable development in hand at present is the pump storage scheme at Loch Awe. This will comprise four 100 MW sets, and pumping will be from Loch Awe to an upper reservoir with a storage capacity of 7·5 GWh at a head of 1 100 ft in Ben Cruachan. The estimated cost, excluding transmission, is as low as £38 per kilowatt. It is hoped that reversible-type pump turbines can be used for the first time at this head.

Each successive development from isolated municipal or private concerns has proved an indispensable part in forming the solid foundation upon which to build in the years to come. There is, as yet, no apparent limit to the future of electricity supply, but we can be sure that the great expansions of the future will rest securely on the efforts of the past.

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WESTERN CENTRE: CHAIRMAN'S ADDRESS

By A. C. THIRTLE, Member.

'PUBLIC ELECTRICITY SUPPLY—ITS PAST AND LIKELY FUTURE DEVELOPMENT'

(ABSTRACT *of Address delivered at* BRISTOL 10*th October*, 1960.)

Forty-three years ago I entered the electricity supply industry as an articled pupil to the late Mr. Francis Madison Long, a pioneer in the development of municipal electricity supplies. A brief review of the expansion of the industry since that date provides a background from which its further likely development can be considered.

The Past Forty Years

In 1920 the annual output from all stations in England and Wales was 3 734 million kWh, approximately equal to half the present annual losses in the combined Area Boards' distribution networks. To-day the annual output is twenty-six times that figure, whilst the maximum demand has increased eighteenfold. Each decade has shown steady increases and is worthy of a brief review (Fig. 1).

During the 'twenties electricity supplies multiplied by a factor of 2·4. In 1920, stations still included a large proportion of triple-expansion reciprocating sets mostly coupled to direct-current dynamos, but during this decade the steam turbine gradually took its hold on power station practice. Sets of 5 000 kW output with steam conditions of 250 lb/in^2 and 650° F were considered high-merit plants.

Mr. Thirtle is with the Central Electricity Generating Board (Southern, South Western and South Wales Region).

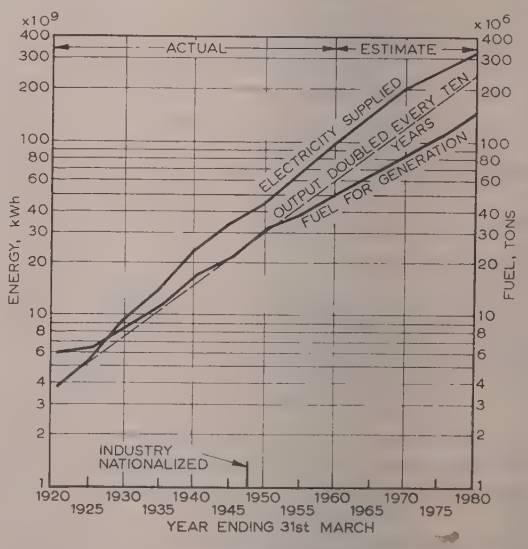


Fig. 1.—Electricity supplied by C.E.G.B. and fuel used (coal equivalent).

When industry started to adopt electric drives more extensively, iability of public supplies became a dominant factor in the nmercial field. Undertakings expanded their power stations d built larger ones, so that by 1930 the total installed capacity the country provided a margin of spare plant of some 80%. The decade of the 'thirties showed a further increase in out-t—by a factor of 2·5. The impact of the 1926 Electricity t, which set up the Central Electricity Board, saw the beginning the 132 kV Grid system. One of the main objectives of this t was the economies to be gained by interconnecting power tions to reduce the amount of spare plant which undertakings d to install to ensure security of supply. The Grid had its sired effect. The proportion of spare plant throughout the untry was reduced to 39·7% by 1939, and further economies ulted from the merit-order loading of plant.

The 'forties were, of course, predominantly affected by war nditions, but nevertheless during that decade consumption creased by a factor of 1·9. The original concept in the design the Grid was to provide the interconnection of generating tions within geographical groups. Separate and distinct areas re controlled from their individual control centres and only a v tie lines existed for mutual support in emergency. During e war the continued need for such support led to running the untry as a single connected system with a co-ordinating tional control.

From the end of the war the planners who were active in many lds gave attention to the electricity supply industry. Com-ttees were formed to report on what should be done to tionalize the multiplicity of electricity undertakings. Most ports agreed that some form of national co-ordination was ential and that the powers of the Electricity Commissioners up under the 1919 Act were insufficient to ensure proper velopment. The Government stepped in and enacted the 47 Electricity Bill, which brought the industry under one tional organization by setting up the British Electricity thority. Some 561 separate undertakings were thus welded o a national organization from the 1st April, 1948.

The most recent and final decade in this historical survey, the ties, shows continued growth in output, the ten-year multiply-g factor being 2·2. The outstanding achievements of this riod have stemmed from the advantages of planning on a tional basis. The provision of generating plant and the sign of the bulk transmission system could now be examined a single exercise, the two fundamental factors being the cation of the source of energy—coal—and the densities of ctricity consumption in the various parts of the country. This dy naturally led to plans for the concentration of generation very large power stations near the coalfields and the trans-ssion of large blocks of power from these coalfield areas to e remainder of the country. A superimposed transmission tem operating at 275 kV was introduced, the first section ming into operation in July, 1953.

During the early part of this decade, whilst planning studies re in progress the installation of standard well-tried plant ntinued. The first break-through to the large high-efficiency nt was the commissioning of the 100 MW set at Ferrybridge B December, 1957, followed by 120 MW sets at Blyth, near wcastle, in December, 1958, and similar sized sets at Drake-v B and Northfleet in 1959. These sets operate at 1 500 lb/in^2 d 1 000° F at the turbine inlet stop-valve, with steam reheating 1 000° F after exhausting from the h.p. cylinder before ntroduction to the intermediate cylinder. Annual operating ciencies of around 34·0% are achieved at these stations.

In the latter part of this decade, on the 1st January, 1958, the ntral Electricity Authority was dissolved and its major nctions were taken over by a newly appointed Central Electricity Generating Board in compliance with the Electricity Act, 1957. This Act made certain amendments to the Act of 1947, resulting, *inter alia*, in giving greater autonomy to the twelve distributing Area Electricity Boards in financial matters. It also set up an Electricity Council to be responsible for certain matters common to the industry and to act as a co-ordinating body.

Let us make a general survey of the changes and achievements of the past forty years. In England and Wales there were 440 power stations in the mid 1920s. By the adoption of larger generating sets, in stations with adequate cooling-water facilities, and the provision of high-voltage transmission, it has been possible to meet large expansion in demand from 234 stations, some of a capacity of over 1 000 MW. Research and practical development by the many British plant manufacturers in the fields of metallurgy, mechanical engineering and electrical technology have brought the benefits of increased size, higher steam conditions and improvements in thermal efficiency. This is clearly demonstrated by the steady rise in the number of units of electricity supplied from one ton of coal. The average figure for Great Britain in 1920 was 585 kWh. This has been trebled so that in 1960 the average is 1 742 kWh per ton at a calorific value of 10 000 Btu/lb.

The transmission and distribution of electricity has likewise shown substantial technical advances over the years. The results are indicated in Fig. 2 by the steady reduction in losses

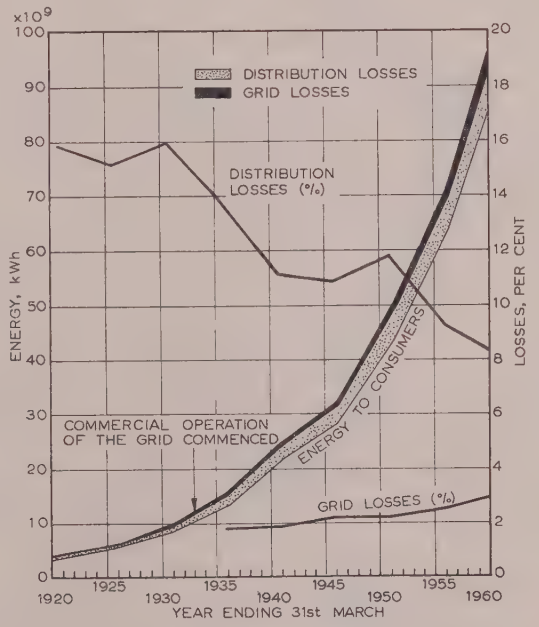


Fig. 2.—System losses.

between the power station output terminals and the consumers' premises. The diagram shows this, admittedly in overall terms, as a graph of the units lost per annum, first by the difference between the units sent out from power stations and the units supplied in bulk to distributors, and secondly by the difference between these bulk units and the units sold to consumers. The substantial reduction in the losses on the distribution systems from 15·9% to 11·1% in the ten years following the introduction of the Grid system is most pronounced. The increase in these losses between 1945 and 1950 reflects the overloading of distribution networks following the war period when restrictions on capital prevented adequate reinforcement. The present level of 8% of units lost in distribution is still too high and points to

the necessity for capital expenditure on reinforcement. The rise in the Grid transmission losses from 1·9% to 2·8% since 1940 reflects the increase in bulk transmission. This is a penalty which has to be paid for the economies gained from generating near the coalfields. The higher voltage to be used for main transmission in bulk over the Supergrid should reduce, or at least avoid an increase in, these losses.

The increase in the scale of operation has markedly affected the number of employees. Today the sales of electricity per person employed in the electricity supply industry in Great Britain is, in round terms, four times the corresponding figure in 1920.

The Present

Planning on a 5–7 year basis is made annually, and the firm programme of generating plant for commissioning up to 1965 shows that some 11 500 MW of new plant, less the scrapping of some old, will increase the C.E.G.B. output capacity to some 37 500 MW by 1965. Fifty-five per cent of this new plant will be built at ten new conventional stations, seven of which are sited on coalfields; 21% will be installed by extensions to existing stations; 3% at the hydro-electric scheme at Rheidol and pumped-storage scheme at Ffestiniog; and the remaining 21% at the nuclear stations of Berkeley, Hinkley Point, Trawsfynydd, Bradwell, Sizewell and Dungeness (Fig. 3).

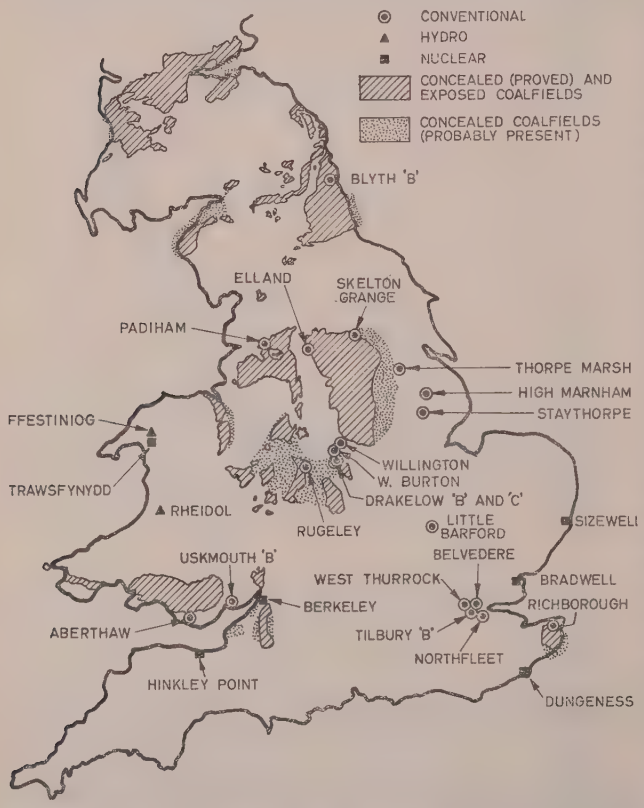


Fig. 3.—Location of coalfields, and planned sites of power stations up to 1965.

This new plant includes sets from 200 MW to 550 MW rating, such large sets now being a practical proposition. A 60 MW set of 1935 had the same relationship to the size of the system maximum as a 430 MW set will have to the demand in 1965.

There are considerable economies in costs to be obtained by adopting large boiler/turbo-generator units of advanced steam condition of pressure, temperature and reheat, and further savings are made in building volumes and consequent costs. Hydrogen cooling and later water cooling of generators has facilitated higher output from the same frame size. Some indication in savings is given by the fact that a turbo-generator unit of 30 MW weighs 8·3 tons per MW, while a 350 MW turbo-generator weighs 3·1 tons per MW.

The capital costs of stations commissioning at the present time is of the order of £50 per kW, less than the figure recorded 12 years ago despite a 70% rise in materials and labour costs. Technological advance is off-setting inflation of costs and will continue to do so in the future. The estimated cost for the Thorpe Marsh station of 1 100 MW capacity (two 550 MW units) is £40 per kW installed.

The advent of nuclear power has modified schemes whereby the bulk of the generation took place at coalfield stations and transmission was over a 275 kV network to high-load areas. Since fuel transport is a minor factor in the operating costs of nuclear stations they can be sited more in relation to load density and in the high-coal-cost areas. Thus one can visualize the Grid receiving its input from and mutually supporting the conventional stations on the coalfields and the nuclear stations in the South and West.

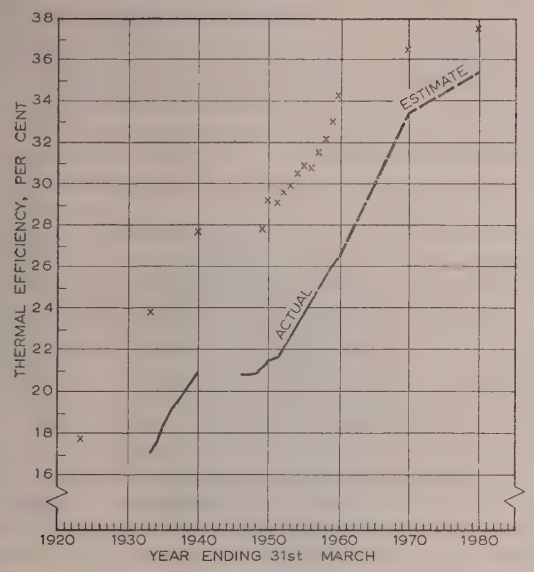
The Future

We can be certain that the consumption of electricity will continue to increase and that there will be no shortage of energy sources. From experiences in such countries as Sweden and the United States it appears most likely that the increase will be along the projected line of the past twenty years. The present plant capacity in England and Wales will need to increase fourfold by 1980. This would require 44 new stations, each of 1 500 MW capacity, plus the replacement of the present plant as it becomes unserviceable. Such a probability poses many problems in finding sites for such a number of large stations, and the maximum utilization of sites by adopting large units at very high steam conditions is essential.

The transmission of the output of these stations to the load centres along routes acceptable to the public becomes increasingly difficult. In order to make fuller use of existing routes uprating of sections of the Supergrid to 400 kV is already planned.

Further improvements in thermal efficiency and cost reductions are limited by the law of diminishing returns. In the development of the steam turbine we have seen the average thermal efficiency trebled in 40 years. There are limits to the further development of the Carnot cycle, but there is still room for improvement in the average results for all stations. Considerable effort is therefore being expended on improving the day-to-day techniques of operation so as to bring the everyday running performance nearer the test performance of machines. Improved instrumentation enables the running losses to be assessed more accurately. The setting of standards of performance by the optimization of losses is improving operation. A number of stations are today achieving monthly results of 98% of the target efficiencies determined by their design performance. The difference between highest individual station and overall system thermal efficiency is shown in Fig. 4. Since an improvement of 0·1% in the average efficiency of the plant on the Generating Board's system at present means a saving of over £800 000 per annum, the efforts are well worth while.

The fuel pattern for the future can be little more than an intelligent guess, but assuming reasonable improvements in performance and the development of nuclear power as foreseen today, the consumption of fuel is likely to follow the pattern shown in Fig. 5.



ig. 4.—Annual average thermal efficiency of steam stations, England and Wales.

——— All stations.
× Highest individual station.

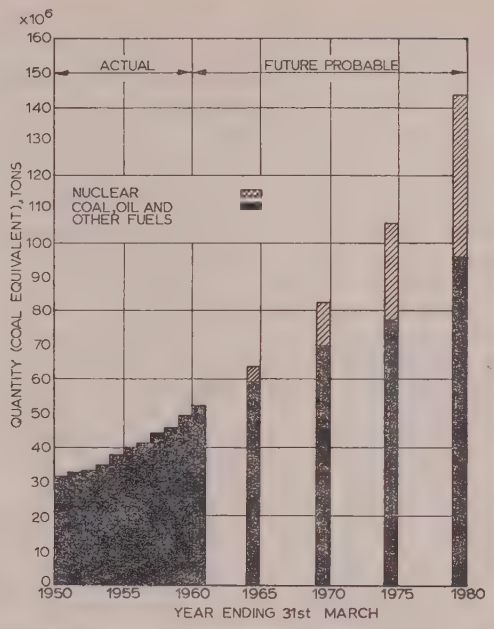


Fig. 5.—Fuel for generation in steam stations: coal equivalent at 11 000 Btu/lb.

National coal production appears likely to be about 200 illion tons per year, and it is reasonable to assume that the uel used for public electricity supply by the C.E.G.B. will ncrease from the present 20% to about 48% by 1980. By that me nuclear-fuelled stations might well be supplying 33·5% of he C.E.G.B. output.

Other factors affecting the pattern of future technical develop-ent are:

(*a*) The problem of low load factors. With the system load factor of 47% the development of short-period-rating prime movers such as the gas turbine will be closely watched, as such plant could make a contribution to solving the problem of meeting peak deamnds.

(*b*) The continued efforts to reduce the costs of supply.

(*c*) The possibilities of new method of generation such as 'direct energy conversion'.

The supply industry has always undertaken a considerable mount of research either directly or by fostering the work of utside bodies, but the importance of research and its effect on he future operations of the Generating Board caused them to et up a Research and Development Department under the direc-on of a full-time member of the Board. This organization is quipped to deal with problems arising in the techniques of generation and transmission of energy. The Central Laboratories at Leatherhead, the Nuclear Laboratories at Berkeley and the Regional Research and Development Units will be co-ordinated by a strategic group of specialists at the Board's Headquarters.

An Applications Branch has also been formed, whose aim is to develop feasible techniques into economic engineering application. One project is the study of more direct methods of converting fuel energy into electrical energy, and involves the consideration of fuel cells, thermo-electric, thermionic and magneto-hydrodynamic generators. A second project considers the hydraulic transport of coal, which promises to cost less than transport by rail if maintenance costs can be kept low. A third project is the automatic control of the supply system, which involves the use of comprehensive computers to give speedy solution to the conflicting issues of economic generation and security of supply. All these new techniques are aimed at achieving continuous operation close to the ideal economic results of design conditions.

The future is full of promise of fascinating new technical development and will depend largely on the abilities, foresight and imagination of young engineers and scientists who are attracted to this vital public service.

[The Address was illustrated by 50 colour slides and a film entitled 'An Interim Report on the Construction of Three Nuclear Power Stations'.]

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EAST ANGLIAN SUB-CENTRE: CHAIRMAN'S ADDRESS

By E. A. FOWLER, Member.

'ELECTRICITY IN THE SERVICE OF MANKIND'

(ABSTRACT *of Address delivered at* CAMBRIDGE 10*th October*, 1960.)

The Address covers a broad survey of the developments of electricity in the service of mankind over the past fifty years.

The first section opens with a description, supported with appropriate lantern slides, indicating the growth and availability of electricity supplies to meet consumers' needs. In the early period of development the power industry faced numerous problems, vested interests, shady speculators and frequent dissension within the industry itself. Most power engineers were called upon to design much of their own equipment, and also that for the users of electricity, in order to ensure the commerical success of their electricity undertaking.

The illustrations forming part of the Address reveal at least four important facts, which may be summarized as follows:

(*a*) Electricity supplies have been made abundantly available in all parts of the country on an ever-increasing scale, and, in fact, the present average rate of demand is such as to double the power requirements approximately every ten years.

(*b*) The economics must have proved to be sound, both to the electricity supply undertakings and to the consumers alike, for the usage of the service to progress at this astonishing rate.

(*c*) The voltage and frequency of electricity supplies, despite a most difficult time in the early years of development, have increasingly become standardized, which has made it possible for power equipment, lamps and domestic appliances to be now freely used in all parts of the country. Clearly, too, the manufacturing concerns have equally kept in step with consumer demand and power development to meet such requirements.

(*d*) The price paid for electricity has been maintained at a consistently low level, and at the present time, despite severe general price increases, remains highly competitive with other fuels.

The development of the utilization side of the industry is then reviewed, covering the same period and supported by illustrations, which were selected to emphasize the great design progress made in the various domestic electrical appliances used in the home, and also industrial and commercial buildings.

Reference is made to the contributory part played by The Institution, the Electrical Development Association, the Electrical Research Association and the Electrical Contractors' Association.

Diagrams indicating the present rate of consumption and saturation of equipment show that, whilst great progress had been achieved, the industry is still a long way from full saturation.

The Clean Air Act is giving added impetus to the full-scale development of electric heating in all modern firms, and the additional advantages of well-designed installations using the special non-peak tariffs now available are clearly indicated.

The need for more adequate wiring installations is stressed and the shortcomings in this matter are brought to light. Reference is also made to the minimum standards of electrical installations as called for in a Post-War Building Study, and it is suggested that these are now inadequate if full electrical development is not to be stultified.

Reference is made to the developments likely to be commercially available in the near future, and the importance of the increasing use of semiconductor materials was demonstrated on a series of models.

An experimental cold box of thermo-electric design was displayed, together with a 30-cell unit operating from a 2-volt d.c. supply, enabling small quantities of water to be frozen in less than a minute. The small current consumption and lack of moving parts clearly brought out the advantages to the user, both in running costs and maintenance.

The electrical luminescent screen was also demonstrated, providing illumination from a tiny battery and transistorized h.f. oscillator unit.

Full-size fluorescent tubes now used in traction services were displayed taking supplies from a 24-volt battery in circuit with a miniature transistorized h.f. circuit.

For use where a solid-fuel fire is considered absolutely essential, a new form of electric firelighter was demonstrated which is now commercially available; this is capable of igniting most fuels in an open grate in 1–2 minutes, thus eliminating the need for any piped gas service.

Mr. Fowler is with The General Electric Co., Ltd.

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NORTH SCOTLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By L. F. DORWARD, B.Sc.(Eng.), Associate Member.

'THE DEVELOPMENT OF THE INDUCTION MOTOR, WITH PARTICULAR REFERENCE TO ITS SPEED CONTROL'

(ABSTRACT *of Address delivered at* DUNDEE 27*th October*, 1960, *and* ABERDEEN 28*th October*, 1960.)

The birth of the induction motor cannot be credited to any one person. It has slowly developed from phenomena which were not recognized at the time of discovery as being sign posts to a new source of motive power. In 1824 it was shown by Gambey and independently by Barlow and Marsh that the oscillations of a compass needle are damped more rapidly if the compass is brought close to a mass of metal. The following year it was shown by Arago that, if a copper disc is slowly rotated above a compass needle, the needle will be deflected. An explanation of these phenomena was provided by Faraday's discovery of electromagnetic induction in 1831.

It was nearly 50 years before these phenomena were exploited to produce a source of motive power. In 1879 Walter Bailey demonstrated an arrangement consisting of four magnetic cores arranged in a circular pattern, the magnetizing coils wound on the cores being supplied from a rotating commutator, giving rise to a rotation of the polarity between the cores. The resulting rotating magnetic field caused rotation of a pivoted copper disc

Mr. Dorward is at Robert Gordon's Technical College, Aberdeen.

iced in the field. The results of this work indicating that Bailey d grasped the fundamental principle of the induction motor.

In 1883 it was shown independently by Marcel Deprez and ofessor Ferraris that the rotating magnetic field can be oduced direct from a single-phase alternating voltage supply the use of two windings with their axis at right angles, the ndings being supplied with currents in quadrature, thus minating the requirement of the mechanical commutator used Bailey.

Credit must be paid to Elihu Thomson and Nikola Tesla for eir work between the years 1887 and 1891 in the laying of the undations of a practical form of motor. Subsequent improve-ents were made by C. E. L. Brown, and motors of his design, corporating Dobrowolsk's invention of the squirrel-cage rotor, re being manufactured with ratings of up to 250 h.p. by 1893.

It is significant that up to this time the emphasis in the develop-ent of the motor had been concentrated on the single-phase achine. The feeling, at least in this country, appeared to be at the 3-phase motor, and indeed the use of 3-phase power nsmission, was merely a passing novelty.

The first serious attempt at a theoretical analysis of the motor as presented by Professor Gisbert Kapp in 1894. Heyland esented his circle diagram approach the following year, hrend developing from this the more refined form of circle agram still in use today.

During the early part of the present century the trend in the velopment of the motor was considerably influenced by the ry demanding limitations on the starting current laid down by e supply authorities. Where the motor was required to start nder load there was a tendency towards the adoption of the p-ring machine, although techniques were, nevertheless, vised to allow the continued use of the squirrel-cage rotor. any ingenious but unsuccessful attempts were made to limit e starting current utilizing the skin effect with the use of com-und rotor bars. More successful methods that were adopted ere with the use of a friction clutch between the machine and e load, or by the use of the double-cage rotor.

With the exception of the spherical motor there has been no ndamental change in the form of the machine since the 1920s. hanges that have taken place have been mainly constructional, r example in the introduction of the welded or fabricated yoke. ther changes have been in the design of stator windings, rticularly for the application of pole-changing techniques.

The induction motor, whilst having the advantages of rugged construction and comparative simplicity and cheapness, suffers the disadvantage of being an inherently constant-speed machine. Many solutions of this defect have been investigated, but most of these result in a more expensive machine due to the capital cost of auxiliary devices and/or a reduction in efficiency at reduced speeds. The following methods of control are reviewed in the Address, the selection being made with the intention of showing the breadth of ingenuity which has been applied to this problem of speed control. Methods regarded as being only of academic interest are included with the view that some of these may form the basis of a more practical solution in the future.

(i) Pole changing methods applied to

(*a*) Conventional squirrel-cage machine.

(*b*) Double-rotor machine.

(*c*) Sliding-rotor machine, in which a smooth speed variation is obtainable by the graduated change in the number of poles over the length of the stator. The machine suffers the disadvantages of having a very limited speed range and increased I^2R and iron losses due to the excessive length of the stator.

(ii) Rotor-resistance control, with its disadvantages of inferior speed regulation and low efficiency.

(iii) Krämar method incurring considerable capital cost in auxiliary machines.

(iv) Cascade systems which again incur increased capital cost.

(v) Unbalanced rotor-impedance operation. This method allows operation at only two speed levels and suffers the further and serious disadvantage that sub-harmonic currents are induced in the supply lines. A solution to this latter defect has, however, been suggested fairly recently.

(vi) Spherical induction motor, whilst perhaps the most ingenious method so far devised, unfortunately has not proved to be as successful in practice as had been anticipated.

(vii) Two methods investigated by the author are also described:

(*a*) Control of a single-phase motor supplied from a thyratron frequency changer.

(*b*) Speed control by variation of the supply voltage achieved by the connection of thyratron-shunted inductances in series with the stator input.

Other methods of control which have been investigated include the use of an eddy-current clutch between the load and the motor; saturated transformers to give a third harmonic and hence treble the motor speed; a resonant circuit connected across the rotor slip rings; and saturable reactors in series with the stator leads.

These and many other solutions to the problem have been investigated, and doubtless many more ideas will be conceived and exploited in the years to come.

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SOUTH-EAST SCOTLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By I. S. FRASER, B.Sc., Member.

'THE ROYAL DOCKYARDS FROM THE ELECTRICAL POINT OF VIEW'

(ABSTRACT *of Address delivered at* EDINBURGH 18*th October*, 1960.)

There are now four Royal dockyards in Great Britain, ortsmouth, Devonport, Chatham and Rosyth, having a total ndustrial labour force of about 43 000 men and women. ortsmouth and Devonport, each employing about 14 000, must e considered quite large. Dockyards undertake a wide variety f work in refitting and repairing ships of the active and reserve leets, and manufacturing capacity for much of the equipment tted in ships must be provided. They also serve as naval bases r the Fleet and provide facilities for berthing, fuelling, storing, mmunitioning and victualling the ships.

Under a recent reorganization, the responsibility for installation and maintenance of electrical and mechanical equipment in Admiralty shore establishments has been transferred to a new integrated department known as the Navy Works Department, which employs professional civil, electrical and mechanical engineers with appropriate industrial labour forces.

The dockyards are popularly supposed to have been founded by Henry VIII. In fact, Chatham was founded by Elizabeth I and Devonport was established in 1690. Rosyth, the most modern of the home yards, was put into operation in 1915, reduced to a 'care and maintenance' basis about 1926 and reopened in 1939.

Mr. Fraser is in the Navy Works Department.

Control at the Admiralty of the dockyards is vested in the Director General of Dockyards and Maintenance, who is responsible to the Board of Admiralty for the programme of work and their organization, efficiency and control.

The internal organization of the dockyards has evolved to meet the changing needs of the Navy, and there is now in process a reorganization from the traditional departmental basis to a functional basis. In the traditional organization, local responsibility and control of the dockyard rests with the Admiral Superintendent who exercises his authority through the agency of the managers of the departments. The three main departments—the Constructive, Engineering and Electrical Engineering Departments—provide the main productive capacity of the yard. Each department is virtually self-contained with its own workshops and other facilities.

The organization of the main professional departments is broadly similar; that of the Electrical Engineering Department, Rosyth, is described in detail in the Address.

The financial control of the dockyards is a budgetary one, based on annual estimates submitted by the yards, revised as necessary at the Admiralty in the light of Fleet requirements and Board policy. Subsequent to parliamentary approval of the Navy estimates, the yards are informed of the amounts allocated for wages, etc., for the ensuing year and given a programme of work.

Apprentice training receives great attention, and each dockyard has its own technical college, attendance at which is compulsory during the first two years of an apprenticeship, further attendance leading to O.N.C. and H.N.C. standards.

The procedure and execution of ship repairs has benefited materially in recent years following the application of method study and similar techniques. Planning offices have been set up at all levels and all work is systematically progressed.

Some years ago a system of planned preventive maintenance was introduced in the Electrical Engineering Department at Rosyth. This has been increasingly successful in keeping plant running and avoiding expensive breakdowns, and the system is being extended to the Engineering Department.

When electricity was first introduced into dockyards early in the century, the policy was that each yard should be entirely independent and self-supporting. Each yard was accordingly equipped with one or more generating stations, substations and a distribution system. At Rosyth, three horizontal steam turbine-driven tandem generators, each of 220 volts, were installed to supply a 440-volt d.c. 3-wire system. Steam at 180 lb/in^2 was supplied by seven Babcock boilers, each of 1 200 lb/h capacity.

When the Admiralty decided that dockyards could rely on supplies from the Grid, supplies were taken from the South of Scotland Electricity Board's 33 kV network through two intake substations over a mile apart, each rated at 10 MVA. The modernized dockyard network at 11 kV has 20 substations and a 6 kV 60 c/s 3-phase ring main for the sole purpose of shore supplies to ships.

Normal consumption runs at about 20 million kWh per annum.

The dockyard telephone system at Rosyth consists of a 1 000-line automatic exchange with manual boards. Direct subscriber lines are provided to all offices and workshops within the dockyard and to certain nearby establishments.

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SHEFFIELD SUB-CENTRE: CHAIRMAN'S ADDRESS

By E. J. LILLEKER, A.M.I.Mech.E., Associate Member.

'ELECTRICAL CONTRACTING IN COMMERCE AND INDUSTRY'

(ABSTRACT *of Address delivered at* SHEFFIELD 19*th October*, 1960.)

The installation engineer—or electrical contractor as he is more commonly known—is surely the Cinderella of the whole electrical family. He has neither the glamour of his intellectual big brother—electronics—nor the popular appeal of his other relative—atomics, and yet in his own specialized way he is a vital link in the family chain. In addition to carrying out his main installation work, which has most probably been obtained on a competitive basis, the electrical contractor has to be prepared to serve as handmaiden to all other trades engaged upon the equipping of a building, particularly specialist subcontractors such as heating, ventilation and telephone engineers. His primary duty is to see that the final job conforms to the Regulations for the Electrical Equipment of Buildings issued by The Institution of Electrical Engineers. With this in mind, together with the client's requirements, the installation can proceed.

Commercial Buildings

To obviate the dire consequences of an aftermath of trailing flexes, piled up socket adaptors and plugs, and surface additions of extra power and lighting points, the contractor and the architect should co-operate in the initial planning stages of a building with a view to the provision of

(*a*) Ducts for the conveyance of the essential services such as water, heating electricity, telephones and the like.

(*b*) Trunking system for accommodating socket-outlets, telephone points, either run on walls or in floors.

(*c*) Suspended ceilings for recessing lighting fittings; also concealment of conduits for the various equipments.

Flexibility of the electrical installation is a very necessary feature, particularly in modern large blocks of offices where they are engaged in financing and kindred activities. Electrical typewriting and accounting machines are continually being introduced.

The introduction of underfloor heating on a considerable scale is to be seen in many offices. The cleanliness and convenience, space availability and initial saving in capital expenditure would appear to outweigh the higher running costs and reduced flexibility which might be incurred.

At present we are not ventilation minded, and the prevalent attitude would seem to be to wait until the building is occupied and then think about fans if and when the atmosphere becomes unbearable. The client should be encouraged by the electrical contractor to consider ventilation as an important feature of the building. The equipment depends largely upon electric supply and control.

A number of different wiring systems have been available for very many years. It is important that the installation engineer should recognize the advantages to apply them properly. A combination of a conduit system enclosing p.v.c.-insulated cables,

Mr. Lilleker is with Lilleker Bros., Ltd., Rotherham.

neral-insulated copper-sheathed cables, and a skirting or or trunking system is often chosen to advantage. Mains bles should be run inside service ducts; the type selected pends upon building construction and purpose of building.

Industrial Installation

Light Engineering.—Examples of light engineering are aircraft mponent works, joinery, sections of the chemical industry, and achine shops. Plants in this category demand frequent connections and reconnections to the electrical service as ocesses are revised and changed to line up with improvements production flow and modernization of techniques. Flexibility important, and consideration should be given to an overhead inking system or a floor-duct system.

Heavy Engineering.—Railway engineering works and machine ops engaged on the heavier sides of electrical and marine gineering have large-capacity electrical drives which are not ble to positional fluctuation. Owing to overhead travelling anes and similar equipment, the electrical services have to be nfined to the structural stanchions and girders, the cables ing supported on traywork or hangers, distribution gear on ames secured to main stanchions, and services to individual achines conveyed along purpose-made floor trenches.

Static Plant.—Under this heading, I refer to plants engaged on a continuous-flow process turning out one particular oduct from the basic-materials stage. Examples are continuous r and strip mills in steelworks, chemical plants, and bakeries prepared-food factories. Each process has its own individual aracteristics, and the electrical installation must be planned withstand the rigours imposed by its own inherent conditions, ch as liability to mechanical damage and effects of atmosphere. I will now enlarge upon a particular kind of static plant, from e points of view of physical operation and electrical installation, d as the plant is not associated with the basic industries of the uth Yorkshire area, I feel sure it will be of interest to members.

The Modern Bakery

Electricity has increasingly powered the automatic machines which provide our daily bread. Flour is delivered in bulk tanker transporters and transferred to storage silos by blower and suction machinery. The flours of various kinds are automatically blended and sieved and passed to automatic weighing machines; then, with other essential ingredients, into the dough mixers. From the mixers the dough is moulded and divided and passed into the first prover for approximately 15 minutes. It is then redivided, tinned, and passed into the final prover for 50 minutes before entering the travelling oven to be baked for about 40 minutes. Still automatically, the loaves are depanned, passed through a cooling plant and finally sliced and wrapped before being loaded into vans for distribution.

A bakery producing 5400 loaves per hour has a total electrical demand of 250kVA.

The fermenting, proving and baking times are all based on natural changes in the dough, so it will be appreciated that any hold-up of any section of the process could ruin a whole cycle of production, causing a complete waste of ingredients. An alternative supply of electricity for use in the event of mains supply failure is very desirable, or at least an emergency supply for essential plant alone.

Owing to the high degree of humidity in bakeries, mineral-insulated copper-sheathed cables with sealed and glanded terminations are most suitable.

Mechanical and electrical equipment requires constant care and maintenance, and there must be a planned scheme for this.

Ventilation presents a complicated problem. The present solution is a large high-level intake fan distributing air through a canvas stocking running the full length of the bakery, coupled with a series of small extract fans at selected positions.

Standardization

Before concluding, I will say a word on a matter common to all installations, both commercial and industrial. There is a wide variety of choice of different types of equipment, all performing the same function, the cost varying immensely. It would ease the contractor's task considerably if such equipment could be standardized.

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SOUTH-WESTERN SUB-CENTRE: CHAIRMAN'S ADDRESS

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By F. C. ISAAC, Associate Member.

'ELECTRICITY SUPPLY IN EAST CORNWALL'

(ABSTRACT *of Address delivered at* PLYMOUTH 19*th October*, 1960.)

The East Cornwall District, which borders on the Tamar, onsists of approximately 320 sq. miles and comprises six small owns, Liskeard, Looe, Torpoint, Saltash, Callington and aunceston, all of approximately equal size.

Looe is quite a well-known holiday centre; Liskeard, Callington and Launceston are market towns and important meeting laces for the farming community; and Torpoint and Saltash re dormitory towns for the City of Plymouth. The provision f a good and adequate service in such a scattered area presents any problems, both from an engineering and a commercial spect, particularly in view of the lack of inter-town public ransport, and the placing of personnel at strategic points roughout the area is essential to give a quick and efficient local ervice.

Mr. Isaac is with the South Western Electricity Board (Cornwall Sub-Area; East Cornwall District).

All the towns obtained their first supply at about the same time, from small generating plants, in the years 1924 to 1926. These small plants operated until a bulk supply was afforded.

Bulk Supply

In 1932, the Cornwall Electric Power Company made a start on the construction of an 11kV network in the area. A bulk supply was taken from Plymouth by two feeders under the River Tamar, one at Torpoint and the other at Saltash, a small ring being completed via the village of St. Germans. Three-panel switching stations were installed to control spurs to the townships of Looe, Liskeard and Callington, this work continuing until 1936. Sixty miles of overhead lines were erected, 30 pole-mounted or ground-mounted substations were installed, and a considerable amount of l.v. distribution was erected.

Looe, Liskeard and Callington were supplied on spurs, and outages were rather frequent, particularly as the area was exposed to high winds and lightning storms.

In 1934 a start was made on a 33kV ring around the area, with substations at Liskeard, Callington and Launceston, and feeding points into the 11kV system, which was also under construction. After the completion of this 33kV ring the two 11kV feeders from Plymouth were abandoned, all supplies being taken from the new system, and the reliability of the supply was much improved.

In spite of the war, development proceeded as far as limited material and manpower permitted, and in 1942 a start was made on a 33kV overhead line from Lostwithiel to Looe to reinforce the existing 11kV supply. With the completion of the 11kV and the 33kV systems a reasonable supply was now available to the urban parts of the district, and therefore no 33kV reinforcement was undertaken between 1944 and 1950, it being considered advisable to concentrate what capital was available in reinforcing and extending the 11kV network, thus permitting the benefits of electricity to be brought to many more consumers.

In 1950 the load in the district was increasing rapidly, and a breakdown of a section of the 33kV ring would have been extremely serious, so it became necessary to reinforce the system to give a firm supply in the area. This was done by adding another 33kV feeder from a substation in the north of the City of Plymouth. Two cables were laid across the Tamar, just below the Brunel Bridge, to a new outdoor substation at Saltash; one cable was energized, the second being used as a standby and not jointed at either end. Pilot cables were also installed and a balanced-voltage system of protection given to the network. At approximately the same time a 33kV overhead line was erected from Saltash to Torpoint, this being necessary to give a more reliable supply to the Rame peninsular area.

The 33kV network in East Cornwall is linked with other districts in Cornwall, and by 1957 it was necessary again to consider reinforcement to the 33kV system to give a firm supply to Central Cornwall, and also to cater for the now rapidly increasing loads in the district, as we were now beginning to experience a certain amount of low-voltage trouble. After consultations with the Central Authority, it was decided to break the Plymouth–Fraddon Grid line at St. Germans and construct a 132kV Grid supply point. Control switchgear and two 45MVA transformers were installed with automatic on-load tap-changing equipment; this was completed early this year. During the same period 33kV overhead lines were erected from St. Germans to Liskeard, Callington and Torpoint, and at the moment a line is under construction from St. Germans to Looe to afford a duplicate 33kV supply. Now all the towns in the area are supplied by at least a duplicate 33kV supply. Callington, Saltash and Liskeard, however, have additional linking feeders, and I think it will be agreed that the main background is now at least as good as that in any other rural area, and that tribute is due to the original design engineers who first laid out the system as far back as 1932.

The 33kV network now operates in a series of closed rings, protection being afforded by impedance relays at all the main 33kV substations, together with one-shot auto-reclosing facilities at these points. These relays appear to be particularly satisfactory; for instance, only a fortnight ago a severe lightning storm tripped two 33kV lines out of Callington substation, severely damaging one of them. The protective systems operated correctly, and no consumers lost supply.

Most of the original 11kV network which was started in 1932 is still in existence, although considerably reinforced. We have in the last two years carried out a great deal of maintenance on these lines to bring them up to modern standards. This 11kV system is operated in a series of open rings, with protection by normal inductance relays.

One of our great difficulties in a district of this kind is the large number of isolated premises, each with an occupant convinced that his need for electricity is particularly urgent. The capital cost of providing supplies to these areas is extremely high, but it is essential in this modern age that supplies be afforded to the farms and other dwellings which are remote from the towns. Much rural development work has been carried out in the last five or six years using single-phase 11kV distribution. More than 60% of the farms in the area are now connected to the supply, and a considerable amount of capital is made available each year for rural development. One of the most difficult problems in the district is to phase the work in order that with the capital available the greatest benefit of electricity supply can be given to the largest number of people. With the introduction of electricity to the farm the question of maintenance of supply becomes a matter of prime importance. It is no longer a case of mere inconvenience if a supply is interrupted, but could mean the difference between life and death for numerous small chicks; the difference between gallons of fresh cool milk and churns of sour milk, to say nothing of the discomfort of dozens of cows waiting for milking; and so we have installed pole-mounted high-speed auto-reclosure switchgear to reconnect supplies rapidly after the occurrence of transient faults. In addition we intend installing one-shot auto-closure mechanisms in certain 11kV substations as soon as possible.

The question of communication in the district has also received much attention, and a complete radiotelephone system has been in use for some years. This is invaluable in enabling engineers in the field to keep in touch with the main control during switching operations, particularly under breakdown conditions. Planned maintenance must of necessity be carried out, and so that the consumers may suffer the minimum inconvenience, small portable generators and temporary 11kV interrupter cables are used. These cables have proved a great boon in the district; they can be laid over ground between sections of the line and so allow a supply to be maintained with but a short shut-down for terminal connections, while maintenance work is carried out. Their use, no doubt, will be considerably extended in the future.

The Future

A new road bridge across the Tamar at Saltash is in an advanced stage of construction, and it is thought that this will be available to carry traffic in August, 1961. With this new gateway to Cornwall, it is anticipated that the area in the vicinity of Saltash will expand rapidly, and that there will be a considerable overspill of population from the City of Plymouth into the East Cornwall District; and it is also hoped that a certain amount of light industry may be encouraged to come into the area. In anticipation of the consequent increase in load, we are already planning considerable reinforcement to the 11kV network, and have acquired a number of substation sites which will be developed as and when required.

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NORTH-WESTERN UTILIZATION GROUP: CHAIRMAN'S ADDRESS

By C. AYERS, B.Sc.(Eng.), A.M.I.C.E., A.M.I.Mech.E., Associate Member.

'SOME EFFECTS OF AUTOMATION'

(ABSTRACT *of Address delivered at* MANCHESTER 11*th October*, 1960.)

It has been apparent for some time that the word 'automation' s become of great importance in engineering circles, and it is dent that its use requires some qualification. In many lay- n's minds the term is synonymous with mechanization, but s is not entirely true.

The process of mechanization follows a basic pattern in prac- ally every application. Initially there exist several basic and crete operations. These are joined by suitable links to form continuous chain of events or a complete process. At appro- iate points in the chain an appreciation of the performance is tained to allow human intervention as necessary for correc- n, and at this stage the process of mechanization ends. ould the appreciation of the process be made to control the ocess an automatic or automated plant results.

Thus progress in automation does not involve any basically w concepts but is more accurately defined as a new attitude mind. Taking this broad view a little farther it may be said at automation is the best integrated use of resources, both men d materials, to produce a desired result; but this appears to be e basic definition of 'engineering'. One may say, therefore, at no definition of 'automation' is possible, but that only ogress towards that end can be established.

Apart from the technical problems attendant upon the applica- n of this thought to any process, several other problems have be solved.

Mr. Ayers is with the English Electric Co., Ltd.

The question of economics is always complex and is often finely balanced, being dependent upon such factors as the cost of the ultimate end-product, the return on capital investment, and the attitude of mind adopted by the user. However, it appears to be generally the case that physical effort can be replaced by an automatic process, but that the replacement of mental effort presents a more difficult problem particularly if concerned with decision making.

The integration of man himself into the automation picture demands skill and patience when dealing with such facets as retraining, possible redundancy, and payment by results which in some cases is the only system with which an operator is familiar. A change of attitude towards work on the part of the operator is thus necessary.

The expanding boundaries of technology have presented educational problems in that specialization is now necessary at an early stage in training. While this is necessary in order that technology shall not stand still, it does not appear to be conducive to the development of engineers in the broad sense, who will be required to conceive and carry to fruition schemes of automation which by their very nature demand the close integration of several skills.

While what has been said applies to the industrial environment, it is equally applicable to the office, where there is much that could benefit from an application of the principles of automation.

DISCUSSION ON 'SILICONE ELECTRICAL INSULATION'*

Before the WESTERN CENTRE *at* CHELTENHAM 14*th March, and the* NORTH MIDLAND UTILIZATION GROUP *at* LEEDS 26*th April*, 1960.

Mr. A. Tranter (*at Cheltenham*): The power-factor/frequency aph rises sharply as the frequency decreases below 100 c/s. ill the author explain the reason for this, especially since mains equency must be one of the most important in the spectrum ven?

In addition, it is not apparent why the curves for 150° C, °C and — 35° C do not appear in that sequence. Why is ere a cross-over effect?

Mr. J. Cripps (*at Cheltenham*): My firm has been using sili- nes for twelve years for the insulation of a range of light- eight electric motors, all of which incorporate a completely organic insulation system. All the machines have hot-spot mperatures exceeding 200° C, but although most of the failures these motors have been closely investigated, not one has been rectly attributable to failure of the electrical insulation. Most ere due to the high temperatures adversely affecting mechanical features. In general, it can be said that this range of motors could not have been produced without the use of silicones.

My experience is that silicone-impregnated windings absorb moisture quite readily, but in practice this does not seem harmful as the moisture dries out equally rapidly with no apparent reduction in electrical performance. The insulation resistance of one motor, which had been completely submerged for about two weeks, was restored from a few thousand ohms to 50 megohms in a matter of a few hours' drying out and it was restored to service undamaged.

The two main disadvantages of silicones are their poor resistance to oil and their inferior abrasion resistance. The oil resistance of unmodified silicone varnishes is so poor that in some applications it has been necessary to derate motors in order that varnishes of improved oil resistance could be used, which nevertheless are unable to withstand the high winding temperatures permissible with silicones. The abrasion resistance of silicone-

* DAVIS, J. H.: Paper No. 2814 M, December, 1958 (see 106 A, p. 193).

bonded and silicone-enamelled wires is such that extreme care is often needed in winding. Again, wire manufacturers have introduced modified silicone varnishes having inferior temperature resistance in order to obtain satisfactory mechanical properties.

Mr. J. N. Robinson (*at Leeds*): The curing of silicone rubber by irradiation is mentioned in Section 3, and whilst it is appreciated in the cable industry that this technique is possible, the cost of capital equipment required to produce the necessary high-energy electrons, together with the cost of silicone rubber itself, would result in a product the cost of which would be prohibitive. As most cable factories in the country are 'steam-driven' it would appear that chemical methods of curing are with us for a time.

With modern extrusion methods, line speeds of several yards per minute are possible and the insulated cable has to be wound on to a receptacle at a point not too distant from the extruder, so that giving an electron dose to the insulation of a cable along its whole length could provide complications where a fairly rapidly moving cable was concerned. The cable insulation must be cured before being fed on to the haul-off drum because of the severe deformation which would occur if an uncured cable was fed on in a multi-layer mass.

The great advantage of irradiation curing is that the strong oxidizing agents required for the chemical curing of silicone rubber are unnecessary, so eliminating the danger of 'reversion' which occurs under certain environmental conditions. As reversion is a hazard with silicone-rubber-insulated cables made by the existing process and occurs when the material is heated in a moist atmosphere lacking oxygen, will the author comment?

As far as cold-curing compounds are concerned, these do not lend themselves to normal cable-making techniques owing to the different time requirements before and after extrusion. Before extrusion it is necessary for a compound to be workable in an uncured state for fairly lengthy periods and to be fed into the extruder as required, but after being extruded onto a conductor the compound must cure quickly to ensure that it is hard enough to resist deformation when wound on to the haul-off drum. These two requirements are difficult to satisfy.

Section 4.6 refers to the effect of nuclear radiation on silicone resins and states that these have a much higher resistance to radioactivity than do the silicone rubbers. It is considered, however, that cables containing silicone rubber and lacquer provide, within their temperature range, the best which can be offered in the way of cables which are likely to be subjected to radioactivity, where flexing and mechanical hazards also occur. Grab cables for refuelling machines are now based on silicone-rubber insulation, which has a far higher resistance to radioactivity than has p.t.f.e., and if accidents are likely to occur where the ambient temperature of the cables is raised considerably, it is safer to have an accident with silicone rubber than with p.t.f.e.

It is fair to state that the conditions of radiation met so far have been such that the use of silicone rubbers and silicone lacquers as cable-making materials has always been possible, i.e. the radiation level has never been sufficiently high to preclude their use.

With reference to Section 6.2, I am surprised that p.t.f.e. is 'often' used as an outer cover for silicone-rubber-insulated cables and would have thought that the number of cases is strictly limited. Sintered and unsintered p.t.f.e. tapes can be applied over silicone rubber but would be unaffected at the curing temperatures of silicone lacquer and could not be regarded as providing full solvent resistance for the cable.

Silicone-rubber sheaths, or glass braids and silicone lacquer can be applied over p.t.f.e.-insulated cores to produce small-diameter single or multicore high-temperature cables for aircraft or instrument use. It should be noted that cables insulated with silicone rubber, which are to be braided with an inextensible filament material such as glass, may require a barrier, usually asbestos, between the elastomer and the braid. This is intended to accommodate the thermal expansion of the silicone rubber which takes place during the stoving of the silicone lacquer that must be applied to the glass. This function of silicone rubber may not be fully appreciated and perhaps the author will comment.

Many new types of silicone-rubber-insulated cables are now available and include multicore polychloroprene-sheathed cables for shipboard use. The cores for these cables are made by two methods:

(*a*) Silicone-rubber compound is extruded on to the conductors in the usual manner.

(*b*) Silicone-rubber-impregnated glass tapes are applied by the lapping technique.

A cable for pendant lampholders has also been developed to accommodate the very high temperature which can occur at the lampholders, and it has a much longer life under service conditions than have cables made of other elastomeric materials.

Cables for aircraft, nuclear applications, high-temperature compensating applications and many others have all found a ready use for silicone rubber in conjunction with silicone lacquers, asbestos, glass and Terylene.

Mr. K. W. Prosser (*at Leeds*): In view of the increasing tendency to encapsulate components in synthetic resins, can the author enlighten us on the state of development of suitable solventless silicone resins for this type of application?

Mr. J. H. Davis (*in reply*): In reply to Mr. Tranter, the authors of Reference 5 regarded the rise in power-factor/frequency characteristic of the dimethyl silicone fluids at low frequencies as probably due to traces of ionic impurity. Similar effects were noted for high-grade transformer oil, and the peculiar variation with temperature was thought to be accidental. This explanation seems to be the best that can be given, for it is difficult to envisage a theoretical explanation in terms of molecular structure.

I agree with Mr. Robinson that silicone-rubber cable insulation cannot yet be cured economically by high-energy electrons but this method could be faster than conventional continuous vulcanization by steam. The absence of curing agent in a stock cured by irradiation will certainly reduce the possibility of reversion under severe conditions, though this might still arise from traces of rearrangement catalyst used in manufacturing the polymer. A reduction in thermal expansion during cable manufacture is possible if silicone-rubber stocks with a high percentage of inorganic filler are used, though physical properties, particularly elongation, are adversely affected.

In reply to Mr. Prosser, solventless silicone resins have been developed for use as encapsulating media in a similar way to solventless polyester and epoxy resins, but are capable of operation over a wider temperature range and show characteristically small changes in dielectric properties with varying frequency and temperature. The unfilled resins are prone to stress cracking during cure or temperature cycling, but this can be avoided by using high filler loadings. Filled resins of this type have been used successfully in the United States for encapsulating end windings of high-temperature motors and to a limited extent in the United States and here for special electronic applications.

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THE DEVELOPMENT OF THE 400 kV NETWORK IN SWEDEN

By G. JANCKE.

(*Lecture delivered before the* SUPPLY SECTION 11*th May*, 1960.)

(1) INTRODUCTION

The natural conditions existing in a country play a very important part in determining the detail configuration of its electric power system, although the fundamental problems remain more or less unchanged in different countries. The networks in the United Kingdom and Sweden differ widely from one another in certain respects, but with the growth of load and the accompanying extension of the network the problems encountered are becoming more similar. It is therefore believed that the experience gained during the development of the Swedish power network may also be of interest to British engineers.

Sweden possesses no domestic sources of fossil fuels, but an abundant supply of relatively cheap water power. However, 85% of these hydraulic sources of energy are found in the northernmost part of the country, whereas 85% of the population, and therefore the chief part of the load, are in the south, as shown in Fig. 1.

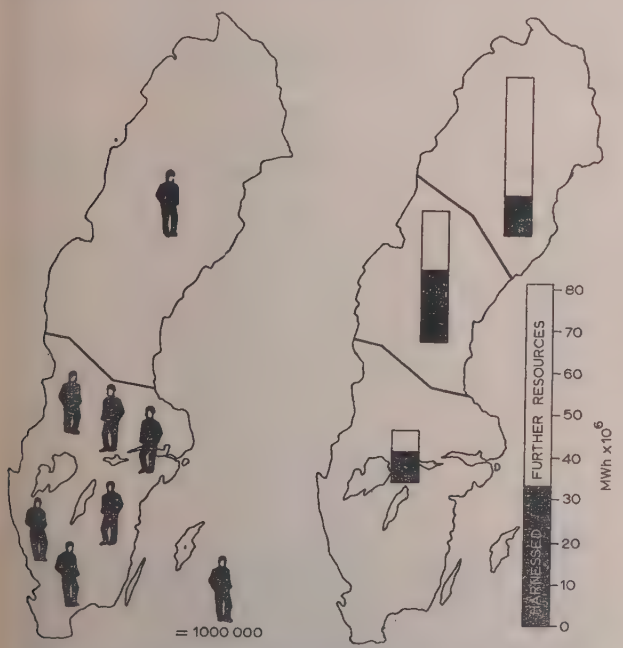


Fig. 1.—Distribution of population and hydro-electric power (1960 stage of development).

This rendered it necessary to transport large quantities of energy over long distances from an early stage of development, so that at the moment about 3 000 MW have to be transmitted over an average distance of 400 miles. It is estimated that within the next 20 years the demand for power will have risen to 8 000–10 000 MW which will have to be transmitted over 500–600 miles. Notwithstanding this long-distance transmission, however, it has been possible to keep the cost of the energy at a low figure, and this has resulted in a high consumption per inhabitant, amounting to about 4·3 MWh annually.

Mr. Jancke is with the Swedish State Power Board.

The power supply is only partially nationalized: the State is responsible for 45% of the supply, while the remainder is in the hands of private and communal power undertakings, although all stations are continuously interconnected. Since 1946 the Swedish State Power Board alone is entitled to construct and operate new lines for 220 kV or higher voltages, but the planning of the main power system is carried out in intimate collaboration with the private undertakings which feed their energy into the State network.

Distribution at 220 kV was introduced in 1936 and this network now comprises 2 800 miles of lines. It became apparent at a relatively early date, however, that 220 kV lines were inadequate for Swedish conditions, and in 1946 it was decided to construct a 400 kV network. The first 600 miles of line, from Harsprånget to Hallsberg, were commissioned in the spring of 1952, and the 400 kV network now comprises 2 000 miles with a distance of 900 miles between the extreme terminal points (see Fig. 2). The installed transformer capacity amounts to about 10 000 MVA.

The conditions existing in Sweden are comparatively simple as regards line routes, the atmosphere is pure, the earthing conditions are very unsatisfactory and the lightning frequency is moderate.

Apart from the choice between a.c. and d.c. transmission and the choice of the voltage, the most important problems in planning relate to the stability, the insulation level and radio disturbances. These problems have been simplified with the growth of the network, whereas the magnitude of the short-circuit power and telecommunication disturbances have become increasingly important instead. We shall deal with these problems here and describe the experience gained and the tendencies followed in the development of the system.

(2) FACTORS AFFECTING TRANSMISSION CAPACITY

The loading capacity of the Swedish transmission system is determined mainly by the stability conditions. Extensive network-analyser measurements and field tests were carried out for the purpose of calculating both the steady-state and transient stability limits for different types of fault and fault location.

Endeavours have been made to obtain the optimum design of the entire system from the aspect of stability. Each part of the system has thus been designed in principle so that the limit costs for an increase in transmission capacity remain the same for all parts of the system.

(2.1) Conductors

The 400 kV lines are provided with bundle conductors to reduce their inductance, the gain being greatest when changing from a single conductor to twin conductors, as shown in Fig. 3. At the same time the field at the conductor surface is weakened, which results in lower corona losses and reduced radio disturbance. The first 400 kV line was equipped with two a.c.s.r.

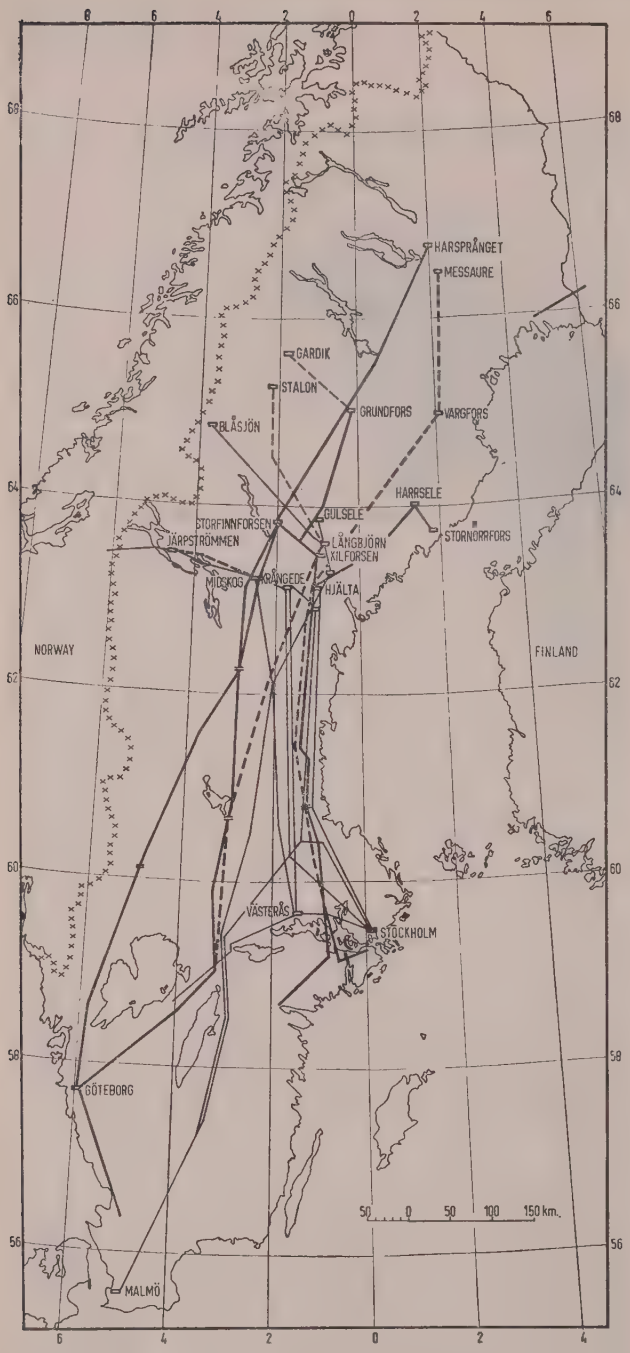


Fig. 2.—The Swedish 400 kV and 220 kV network in 1960.
The broken lines show circuits under construction.
400 kV.
220 kV.

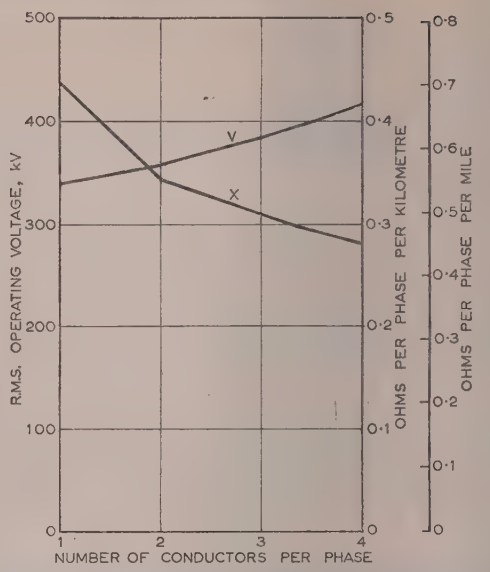


Fig. 3.—Reactance and permissible operating voltage (with regard to radio interference) on single and bundle conductors with the same total cross-section.

conductors per phase, each 1·25 in in diameter and having an equivalent copper cross-section of 0·5 in², to reduce radio disturbances and corona losses. A line of this kind has an optimum loading capacity of 600 MW. Since the load per line can now be increased considerably, owing to the improved stability conditions, the lines are now being built with three 1·25 in conductors per phase and with an optimum loading capacity of 750 MW. The fifth trunk line will be equipped with three 1·42 in conductors per phase, so that the total equivalent copper cross-section per phase will be 2 in² as compared with 1 in² for the first lines. In future the cross-section will probably be further increased to 2·4 in² and the load to 950 MW per single line.

(2.2) Capacitors

The series capacitor (Fig. 4) has brought about a radical improvement in the conditions for long-distance transmission.

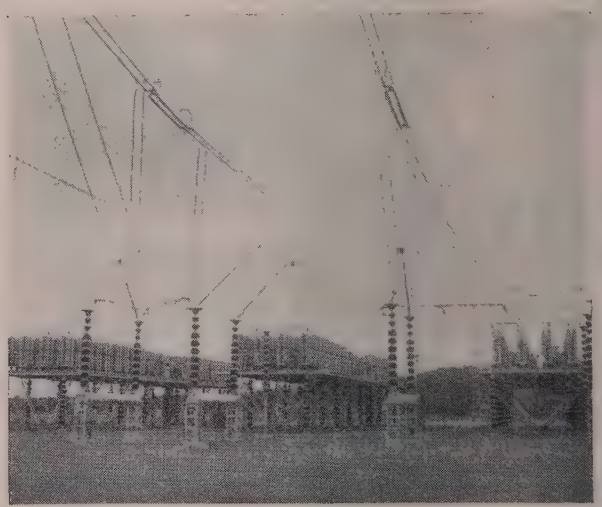


Fig. 4.—400 kV series capacitor for 105 MVAr.

It represents a 'quantitative' medium which can be dimensioned to provide the exact compensation of the line reactance required. With its help the line is shortened from an electrical viewpoint so that under given stability conditions the transmission capacity is increased, and at the same time the distribution of the load between parallel-connected circuits can be improved by compensating them in such a way that the different branches will

have the same reactance in relation to the resistance. By this means the total transmission losses in the Swedish power network have been reduced by 9 MW, the optimum compensation being about 40% in lines with twin conductors and about 50% in the heavier lines. Hitherto, 650 MVAr have been installed in five 400 kV plants and a number of others are under construction. In Sweden it is found most advantageous to place the series capacitors out on the lines, preferably in that part lying nearest the receiving stations. The stations are unattended, but are visited once every two weeks for routine inspection and maintenance. Up to the present, no electrical faults have occurred in these installations, the first of which has been in service since 1954. They have reduced the transmission costs per kilowatt-hour by about 15%. When considering other measures relating to the promotion of stability, the costs of the series capacitors are taken as a basis for an economic comparison.

In the power stations the reactance is reduced by choosing transformers with a low short-circuit voltage, and it has been found suitable to employ about 10% reactance in the step-up transformers. On the receiving side auto-transformers are installed between the 400 kV lines and the local 130 or 220 kV networks. For the larger generators a transient reactance of 20–25% was adopted at the outset, and it later proved possible to increase this. The generators are equipped with quick-acting regulators of the transductor type. The introduction of rectifier excitation combined with electronic regulators was contemplated, but the utility of this arrangement has now decreased, so that it is no longer economic.

(2.3) Switchgear

Three-pole high-speed reclosure is employed with satisfactory results in the 400 kV network, the dead interval being 0·4 sec. The method can be adopted where a number of parallel circuits are available, so that the mutual phase position between the two ends of the line changes only slightly during the dead interval. Where a single line is in question, single-pole high-speed reclosure becomes of considerable interest for the promotion of stability. Field tests have shown the method to be applicable at 400 kV for line sections up to 175 miles long, and the method is now being introduced for such lines.

In the first stage of the 400 kV network the stability was somewhat strained and it was important that the rupturing times on short-circuits should be as short as possible. With this end in view, circuit-breakers with a rupturing time of less than three cycles and relay protection with a functioning time of one cycle were employed. The conditions are no longer so critical and importance is now placed more on the reliable mechanical functioning of the circuit-breakers than on extreme rapidity. Three cycles are now permitted on the relay side, which reduces the risk of unwanted functioning.

In some countries intermediate switching stations 100–150 miles apart are considered to offer a valuable method for raising the transmission capacity. In this respect, however, only the conditions arising on the occurrence of line faults are taken into account. Apart from these, it is necessary to consider faults at the circuit-breakers, unwanted functioning of the relays and human errors: the effect of such faults on the network increases with the introduction of intermediate stations. It should also be noted that the lines must be drawn together at an intermediate station. This may be done in a transmission between a concentrated source of power and a concentrated load area, but in other cases an intermediate station entails longer power lines and therefore increased costs of installation and losses. For these reasons intermediate stations have not been introduced in the Swedish network. With a line section exceeding 350 miles, however, an intermediate switching station equipped with 400 kV shunt reactors would be considered, in order to reduce the operating-frequency voltage rises.

(2.4) Circuit Stability

When the first 400 kV lines were planned it was unreasonable from an economic aspect to demand complete operating reliability, even in the event of the worst faults which might occur on the system. When determining the point of time at which new lines should be installed, therefore, a special cost item was introduced to cover the probable number of total breakdowns in the main power system to which such faults might be assumed to give rise, on the basis of earlier operating experience and theoretical calculations. The costs for disturbances in operation were estimated from a national-economic viewpoint with respect to reduced production and destruction of material and other inconveniences to the country which a breakdown in the supply might entail. This estimate showed a cost which, to-day, would be about 1·5s. per kilowatt disconnected plus 3s. per kilowatt-hour. The design of the system obtained in this way has, in fact, given such an adequate margin of stability that only one major disturbance has so far occurred, and this was caused by a human error.

With an increase in the number of 400 kV lines operating in parallel the costs for achieving full operating reliability have been reduced, although at the same time the extent of a serious breakdown has increased. On this account the network is now built in such a way that it is stable for every fault location. Individual power stations are connected to the main network through single lines, however, since the short-time disconnection of limited generation does not entail a breakdown of a serious nature. Live-line maintenance work is used.

For reasons of stability the first 400 kV lines, comprising two sections of 300 miles each, were loaded with only about 450 MW. It has now been possible to raise the load to 650 MW and it will gradually be further increased to 900–1 000 MW. In step with the foregoing, it has also been possible to increase the size of the transformer banks: from a capacity of 300 MVA (3-phase) a level of about 1 000 MVA has now been reached.

(3) FACTORS AFFECTING INSULATION LEVEL

The choice of the insulation level exercises a considerable influence on the costs and operating reliability of a high-voltage network. For low installation costs it is desirable to choose a low insulation level, but the risk of faults due to flashover or puncture will be increased. These factors can be evaluated under given disturbance costs and included in the economic calculation. In power lines the faults caused by an insulation level which is too low are usually of a transitory nature, or in exceptional cases they may call for repairs which can be executed relatively quickly. On this account one may venture to accept relatively large risks and determine the insulation level to a large extent with a view to the network's capacity to withstand line faults without breakdown of the stability. On the other hand, faults in the station equipment may result in lengthy shut-down periods, and consequently one is unwilling to accept faults of this kind, even when standby transformers are installed to deal with catastrophic breakdowns.

(3.1) Voltage Rises at the Operating Frequency

It is necessary to take into account the conditions which exist under normal service and also the over-voltages which may be set up within the system itself or which may be of atmospheric origin. A minimum requirement is that internal voltage rises must not cause a breakdown in operation.

The internal over-voltages are set up when changing over from one form of operation to another, and they consist partly of the voltage rises at the operating frequency which occur when a loaded line is interrupted, along a line connected at one end, and during single-phase-to-earth faults in sound phases, and partly in transient phenomena and switching over-voltages from the circuit-breakers. The latter are superimposed on the voltage rises at the operating frequency.

System earthing plays a decisive role. For various reasons only direct earthing of each transformer's neutral point could be considered for the Swedish 400 kV network: with any other method the limitation on transformer output set by difficulties of transport would be considerable. It was foreseen that the network would rapidly become so extensive that arc-suppression coils would be unable to extinguish single-phase faults. The costs were very appreciably reduced by the lowering of the insulation level rendered possible by direct earthing.

The voltage rise on interrupting a loaded line is a function of the line length, the available short-circuit power and the load. The effect of the short-circuit power in the feeding station is considerable (see Fig. 5), so long as it is below 2 000–3 000 MVA.

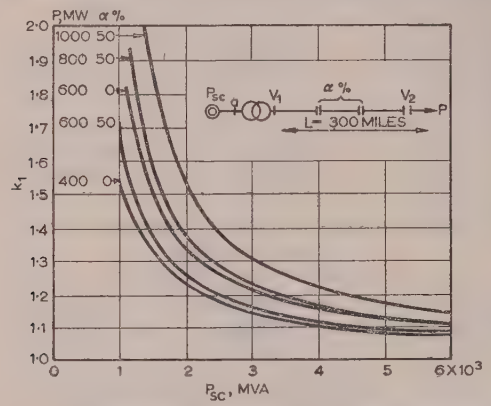


Fig. 5.—50 c/s voltage rise on switching off a 300-mile 400 kV line loaded with *P* megawatts.
P_{sc} = Short-circuit power in connected end, MVA.
α = Series-capacitor compensation, %.

The length of the line exercises less influence, and the installation of series capacitors tends to reduce the voltage rise.

A further voltage rise is experienced at the open-line terminal, owing to the Ferranti effect. Here, too, the effect of the series capacitor is considerable. If the latter is short-circuited simultaneously with the disconnection of the load, however, values will be obtained which correspond to those of an uncompensated line. A shunt reactor connected to the open-line terminal reduces the voltage rise considerably, as shown in Fig. 6.

A single-phase-to-earth fault in the most unfavourable position will result in an additional voltage rise in the sound phases. At the feeding stations it amounts to about 10% with a short-circuit power of 6 000 MVA, and it will be less with lower powers. Appreciably higher values are obtained at the open-line terminal, and here, too, high values are combined with a large short-circuit power in the feeding station, as shown in Fig. 7.

The combination of a single-phase-to-earth fault at a line terminal and the resultant interruption of the loaded line earlier at one end than at the other will be decisive for the stresses on the insulation at the operating frequency.

(3.2) Transient Voltage Rises

Extensive tests have been carried out in the Swedish network with seven different types of 400 kV circuit-breaker, in order to

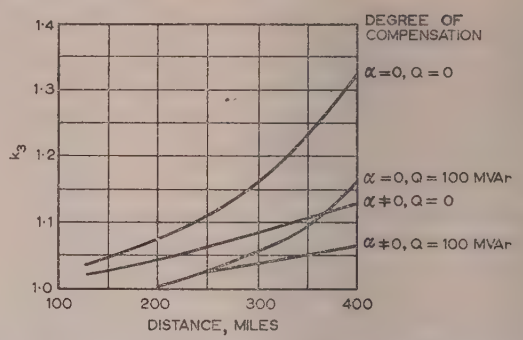


Fig. 6.—Relation between voltages in open-line end and connected-line end as a function of line length.
Values are given for lines with and without series capacitors located symmetrically about the line centre, and with and without a 100 MVAr shunt reactor in the open line end.

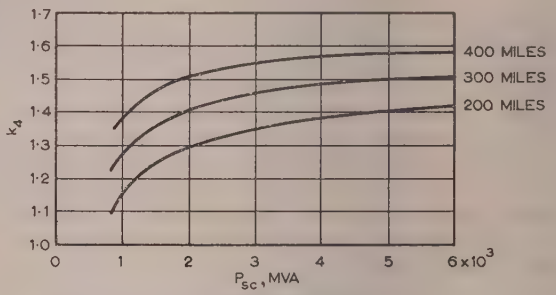


Fig. 7.—Additional voltage rise in sound phases in open-line end when a single-phase fault to earth exists near the end.

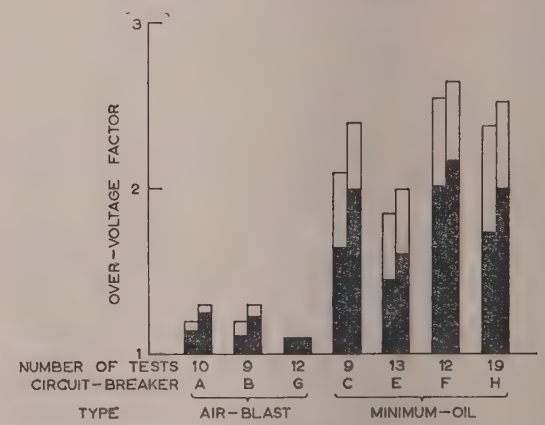


Fig. 8.—Histogram showing the over-voltage factors measured on interrupting a 300-mile unloaded 400 kV line.
Unfilled stem; maximum value.
Filled stem; mean value.
First stem; station side.
Second stem; line side.

determine the magnitude of switching surges in the most unfavourable cases. The results shown in Fig. 8 were obtained when disconnecting a 300-mile unloaded line. The tests were carried out with an operating voltage varying between 400 and 550 kV at the feeding station. The air-blast circuit-breakers were entirely free from restrikes and therefore did not set up any over-voltages; on the other hand, the oil circuit-breaker restruck, which resulted in over-voltage factors up to about 2·5. In addition, a series of voltage jumps with a very steep wavefront were obtained with restrikes, which occurred at extremely short time intervals. These voltage jumps took place symmetrically

around zero potential, so that the arresters were unable to protect the transformers. During the tests on one circuit-breaker, which on account of its total failure has not been included in the Figure, 20 such jumps of about 1·5–2 MV were obtained on one occasion, with a wavefront time of approximately 1 microsec and time intervals of a few microseconds. In the course of this test the transformer in one phase flashed over at the entrance coils. Now, only non-restriking circuit-breakers are installed for the lines, which not only eliminates the risk of such transformer stresses but also lowers the insulation level necessary.

The results obtained when disconnecting unloaded and reactor-loaded transformers are shown in Fig. 9. Here the different

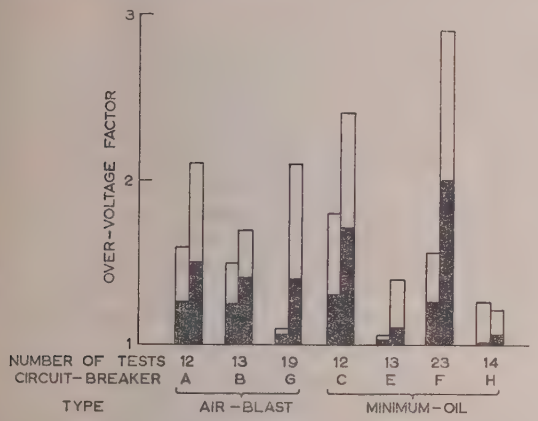


Fig. 9.—Histogram showing the over-voltage factors measured on interrupting a reactor-loaded or unloaded transformer.

Unfilled stem; maximum value.
Filled stem; mean value.
First stem; station side.
Second stem; transformer side.

types are equal to one another, thus improving the freedom of selection. In this case arresters placed on the transformer side of the circuit-breaker can give protection against over-voltages without the risk of being destroyed.

In the transition from a stationary condition to some other state, certain transient oscillation phenomena are set up; these have been studied more closely in a transient analyser and in field tests. They were then found to be harmless for line lengths up to about 300 miles, whereas in a line of 400 miles they produced over-voltage factors of about 2.

(3.3) Atmospheric Overvoltages

When the transformers and cables are protected by lightning arresters, and the switchgear has a somewhat higher insulation than the connected lines and is protected by earth wires, atmospheric over-voltages may be ignored in the choice of the station insulation. On the other hand, they affect the operating reliability of the lines (see Fig. 10). These have been constructed hitherto as single-circuit lines with towers of the gantry type, provided with two steel earth-wires and insulators of the cap-and-pin type. Earthing of the towers has been improved by the use of a continuous counterpoise supplemented by crow's-foot earthing in particularly unfavourable localities. No additional earthing is considered necessary where the earth resistance of a tower is less than 30 ohms for three consecutive towers. The isoceraunic level averages 11.

When the internal voltage rises are taken into account, the insulation level obtained is so high that it is not considered justifiable to increase it further to guard against lightning over-

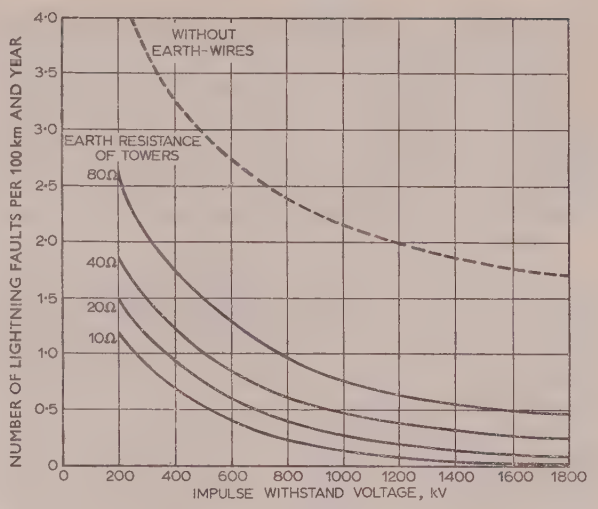


Fig. 10.—Approximate number of lightning over-voltages leading to flashovers at the insulation with a varying impulse withstand voltage for the insulation and with a varying average value of the earthing resistances of the towers.

The curves apply to lines with the gantry type of towers and two earth-wires and to an isoceraunic level of 10.

voltages. A study of their distribution curve shows that only a small number of lightning strokes can give rise to higher voltages and that the elimination of the risk of faults from such causes would necessitate an appreciably higher insulation. This is not economically feasible. Moreover, the 400 kV network has now obtained such a high degree of transient stability that the omission of earth-wires for new lines is being discussed.

(3.4) Normal Service Conditions

Before the insulation level for a power line is definitely determined, a check must be made to see that under normal service conditions the voltage across individual units in the insulator string is not too high. The 1 min withstand voltage in rain is 40 kV for insulators with a $5\frac{3}{4}$ in spacing and 45 kV for those with a $6\frac{3}{4}$ in spacing. Experience shows that it is normally possible in Sweden to work with a voltage across an element which represents 50–60% of this value without the risk of a creeping flashover or a 'morning fault' with moderate pollution.

As may be seen from Fig. 11, the voltage distribution across the insulator string is uneven and the lowest unit receives the

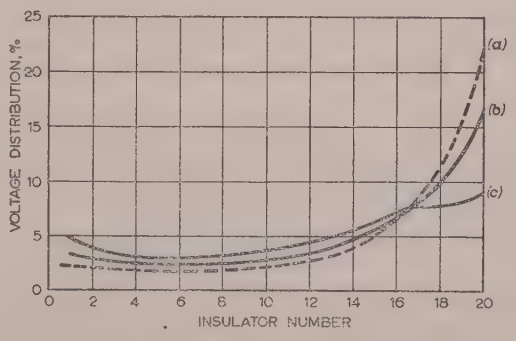


Fig. 11.—Voltage distribution over a 20-unit suspension insulator string.

The unit numbers are counted from cross-arm to conductor.
(*a*) Insulator string without conductor.
(*b*) Insulator string with double conductors.
(*c*) Insulator string with double conductors and shielding ring.

highest voltage. The distribution can be improved by employing a grading ring, although this somewhat reduces the insulation strength of the string.

Normally, a creepage path of at least $\frac{4}{3}$ in/kV of the system voltage is required. When a line runs in the vicinity of the Swedish west coast without being shielded by forest, and is thus subjected to salt deposits, the creepage path is increased to at least 1 in/kV. This can be done by employing special fog insulators or by increasing the number of units in the string.

(3.5) Choice of Insulation Level

In the first stage the insulation level of 1 775 kV was chosen for all station equipment. The lines were fitted with suspension insulator strings consisting of 21 units with $6\frac{3}{4}$ in spacing and with arcing horns and grading rings. This corresponded to a surge-withstand voltage of 1 580 kV and a 1 min withstand voltage of 715 kV in rain.

It has been possible to lower the insulation progressively in step with the increase in short-circuit power in the network, the improvement in the properties of the arresters and the availability of non-restriking circuit-breakers. At present 1 425 kV insulation is employed for transformers and cables and 1 550 kV for bushings and other station equipment. The lines have a surge-withstand voltage of 1 275 kV and a 1 min withstand voltage of 640 kV in rain. In future it should be possible to lower the transformer insulation to 1 300 kV, but before doing so it is desirable to obtain a better knowledge of the insulation ageing due to the operating-frequency stresses and switching over-voltages.

The transformers are impulse-tested with a full wave. It has not been considered necessary to increase the cost of the transformers by calling for tests with chopped waves, since the switchgear is protected against direct lightning strokes by earth-wires; rod-gaps are not used in the installations and only line circuit-breakers of the non-restriking type are purchased.

(4) RADIO AND TELEPHONE INTERFERENCE AND CORONA LOSSES

The Swedish 400 kV lines now in service are provided with two a.c.s.r. conductors per phase, each having a diameter of 1·25 in; they are placed 18 in apart, while the phase spacing is 36 ft.

Radio interference is insignificant and complaints have been received only from a few hundred listeners. The disturbances from conductor corona occur primarily in the long and medium wavebands, whereas they are insignificant at high frequencies. Consequently, television and ultra-short-wave radio reception are subjected to very little disturbance from the high-voltage power lines. The present lines have a maximum field strength of 39·4 kV/in at the conductor surface; this will be appreciably reduced in the new lines with heavier conductors, and should not give rise to any trouble.

It is difficult to state a definite value for the corona losses, since these vary very much with the meteorological conditions. In fine weather they amount to 1 kW per mile of 3-phase line, and the mean annual value is about 5 kW per mile. With three conductors per phase the losses are halved.

On the occurrence of earth faults in the 400 kV lines relatively large e.m.f.'s may be induced in lines running in parallel. Since the bedrock in Sweden is covered with a thin layer of soil, the conductivity of the ground is usually poor and the inductive effect may therefore be considerable. According to calculations and measurements, voltages as high as 15 kV may be obtained in telecommunication lines, and protective measures must therefore be taken. These can be undertaken best and most cheaply on the disturbed side, and chiefly in accordance with the recommendations of the C.C.I.T.T. Normally, the overhead telecommunication lines can be protected by simple surge diverters, in which case the telephone authority permits the installation of a maximum of three diverters per mile. In the most troublesome cases, overhead telephone lines are transferred to cables. When the permissible values for the cables are exceeded, protective conductors of copper or aluminium are buried in the ground along the length of the cable.

In low-voltage lines also, impermissibly high induced e.m.f.'s may be set up; there, isolating transformers are installed as a protection in certain cases.

Sound disturbances do not, as a rule, give rise to trouble, since the telecommunication circuits have double-wire connections and the harmonics in the power-line current are small. According to the C.C.I.T.T. recommendations a transposition cycle of 11 miles is required. The transposition towers entail heavy additional costs at the highest voltage, however, while at the same time operating reliability is somewhat reduced and damping is increased for the carrier-current connection. After negotiations with the telephone officials, permission has been obtained to transpose the conductors for 400 kV practically with regard to the actual requirements on the power side only, and transposition cycles up to 150 miles have come into use.

For installations located in the immediate vicinity of a 400 kV line the electrostatic influence may cause inconvenience. This can be best overcome by earthing all metal objects of large size in the neighbourhood. Petrol filling stations are not permitted in the right-of-ways.

(5) VOLTAGE REGULATION

The Swedish 400 kV lines produce about 900 kVAr of capacitive power per mile. For a line section of 300 miles this amounts to 270 MVAr and about 1 800 MVAr for the whole network. To facilitate the starting up of the lines again after a breakdown and for voltage regulation at low loads, shunt reactors for about 1 000 MVAr have been installed and have been connected in units of 60 or 40 MVAr to the generator busbars or the tertiary windings of the transformers. Since the connection of these units influences the dimensioning of the transformers and increases the load losses in the latter, three shunt reactors for 150 MVAr each have now been ordered, two for 220 kV and one for 400 kV. In future, 400 kV reactors will chiefly be installed.

In addition, 400 MVAr in the form of synchronous machines is available in the receiving stations, which also improves the transmission stability. During periods of low load one of the 400 kV lines is often taken out of service, in order to improve the reactive power balance. The increase in the reactor capacitance chosen will, however, render this line disconnection unnecessary.

A special case is presented by a line section 400 miles long which, when connected on one side, produces about 600 MVAr. This presents certain difficulties in the network from the aspect of voltage and stability. Arrangements have therefore been made, via a carrier-current connection, to enable the line circuit-breakers at both ends to be actuated simultaneously, on both automatic and manual operation. With full load on the network the latter consumes more reactive power than the capacitive generation provides. Shunt capacitors have been installed on an extensive scale. These are usually located close to the load centres.

In principle, the network is driven with a flat voltage, but at heavy loads the voltage at the receiving end is allowed to drop to 380 kV while 400 kV is maintained in the power stations.

The short-circuit power at the 400 kV busbars now amounts to a symmetrical maximum of about 12 000 MVA, and it is estimated that it will increase to nearly 20 000 MVA. On the

low-voltage side of the transformers it is calculated that a maximum of 12 000 MVA will be obtained at 220 kV and 8 000 MVA at 130 kV. At the generator busbars and on the tertiary side in the receiving stations, i.e. at 15 to 20 kV, more than 4 000 MVA is obtained in certain cases. No measures are usually taken to reduce the short-circuit power, since a low reactance is desirable from the viewpoint of stability and for limiting the voltage rises at the standard frequency during abnormal operation. No great difficulties are encountered in purchasing at reasonable prices circuit-breakers and other apparatus which are capable of withstanding these stresses, but the short-circuit withstand strength of the transformers still represents a relatively unknown field.

(6) THE POWER LINES

The Swedish 400 kV lines are designed in the form of single-circuit lines. Since no very large generator output or load is concentrated at any one point, it has not been found advantageous to construct double-circuit lines. Expanded conductors have not been employed, nor is their use envisaged for the future.

The towers are of the gantry type (Fig. 12) which has proved

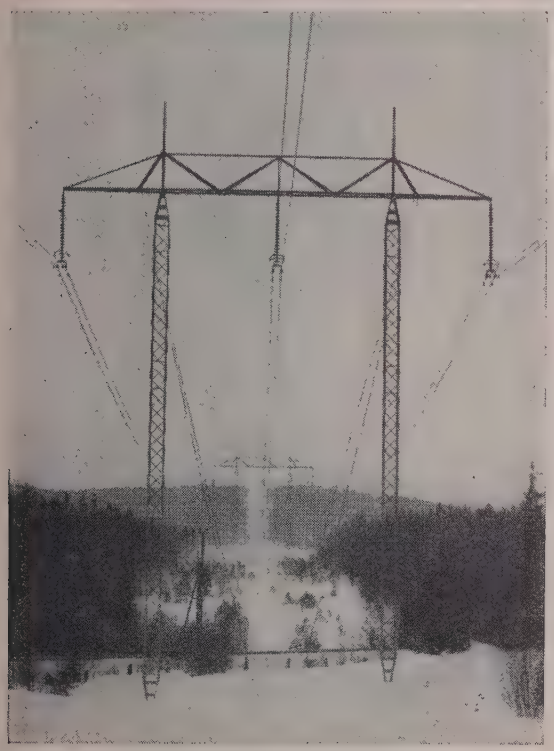


Fig. 12.—Stayed type of tower.

cheaper for the Swedish requirements than the corset type. They are guyed, and the steel weight per mile is 24 tons with twin conductors and 29 tons with triple conductors. Dead-end towers are employed only at the stations.

Cap-and-pin insulators with a $6\frac{3}{4}$ in spacing are used. Both glass and porcelain insulators are employed, the former having the advantage that a faulty insulator can be easily detected without measurement. It has not been found suitable to employ long-rod insulators.

Two earth-wires are installed with a protective angle of 31°. The earthing has been improved by means of a continuous counterpoise. The isoceraunic level averages 11. Lightning frequency has hitherto amounted to 0·18 fault per 100 miles per year, of which 70% have been single-phase and 30% two-phase faults.

Certain fears were expressed in the initial stages concerning the behaviour of the bundle conductors under additional loads of snow, ice or frost. Experience has shown, however, that the conditions have been no more troublesome than in lines with single-phase conductors in the same regions. Heavy additional loads are produced on the average for a week or so about every third year on certain spans which are in an unfavourable location. Deformations have not occurred, but the lines were formerly taken out of service for mechanical de-icing. It is impossible to carry out electric melting, owing to the great length of the line sections. Extra towers have been inserted in a few spans, the normal span length of 1 100 ft being halved. In a number of specially exposed sections spacing rods have been mounted at a distance of 215 ft apart in place of the normal 430 ft, thus eliminating the risk of tilting of the multiple conductors due to unsymmetrical additional loads. The Swedish meteorological service sends out a warning when the weather conditions are such that there is a risk of ice or frost formation on the lines. On such occasions observations are taken with a recording instrument of the damping of carrier-frequency signals transmitted over the power lines. When this damping increases considerably, it is a sign that the line has become coated. Members of the staff are then sent out to the critical points on the line to remove the additional load by mechanical means while the line is under voltage. Live-line maintenance is also carried out when changing insulators and for other simple maintenance operations. Slow-flying aeroplanes are used for inspection to an increasing extent in place of inspection from the ground.

In a few places the earth-wires have been insulated from the towers for one or two miles and are used for lighting aircraft beacons on the tops of the towers. The source of power consists of the capacitive influence from the phase conductors.

(7) THE STATIONS

The experience gained in connection with the operating reliability of high-voltage transformers has been extremely satisfactory. We have therefore chosen very large units whose size is limited only by the possibilities of transport. Nowadays, railway tracks are only laid up to the stations when the latter are located within a distance of a mile or so from an existing railway. Road transport is employed elsewhere, and for this purpose the largest transport truck can take a load of 225 tons.

Sweden is an outstanding water-power country in which the individual power stations are of moderate size. When the output of a station exceeds 300 MW, direct transformation to 400 kV is found most remunerative. For this purpose a common transformer group is installed for all the generators. The largest group of this kind is installed in a station with four 150 MVA generators. In smaller stations the output from a number of stations in one district, such as a river valley, is collected in a 130 kV or 220 kV local system and fed into the 400 kV network through auto-transformers. These transformers are installed in one of the district's largest stations and the generators in the latter are connected to the delta-connected tertiary of the transformer group.

Auto-transformers for 400/130 kV or 400/220 kV are used in the receiving stations, group sizes up to 1 000 MVA being installed. In the first stage a relatively wide range of regulation was chosen for the transformation, on which account separate series-connected regulating transformers were installed on the low-voltage side. Experience has shown that there is only a moderate demand for regulation, and consequently a smal

regulating transformer is now placed in the common directly earthed neutral point. Regulation is omitted entirely in a number of receiving stations and also in the power stations. The synchronous machinery and shunt reactors are connected to a delta-connected winding for about 20 kV.

The transformers consist of single-phase units. Initially, a set consisting of three units with a fourth in reserve is installed. In a receiving station it is far more difficult to make arrangements for a disconnection than in a power station, and consequently in these stations the connections have been chosen so that a unit can be changed on-load by means of circuit-breakers and isolating switches. As the need for transformation grows, the equipment is increased to seven units, whereupon it is usually possible to change a unit with the help of isolating switches during the disconnection of one set, lasting for approximately 20 min. There is a trend to change over to three-phase transformers in moderate-size receiving stations. Hitherto, one 350 MVA 400/130 kV unit has been ordered.

In the power stations, the turbines and generators are usually installed underground for economic reasons. Transformers in the power stations and receiving stations are placed in chambers blasted out of the rock for other reasons. In this case 400 kV cables are employed, which are led directly into the transformers. Lightning arresters are installed in every station and are directly connected to the transformers or the upper ends of the cables. The 400 kV voltage transformers are designed in the form of capacitive voltage-dividers. Separately mounted current transformers are used for the lines, whereas the transformers are provided with current transformers around the bushings or the potheads of the cables.

The switchgear is provided with one main and one transfer busbar. The circuit-breaker of the transfer busbar constitutes a common standby for the other 400 kV circuit-breakers in the station. In some cases circuit-breakers are not installed for short lines and the transfer circuit-breaker is then used for these when it is not needed for other connections. Air-blast circuit-breakers are usually employed; the working pressure for the compressors was formerly 450 lb/in^2, but it has now been raised in some stations to 2 200 or 4 400 lb/in^2.

There has been a tendency for a long time past to replace manual operation control equipment by automatic and remote control. To some extent the otherwise praiseworthy attempt to achieve perfection has led to complications, with the result that the machine hands have had to be replaced by expensive specialists. Endeavours are now being made to reach a more balanced arrangement.

(8) THE NETWORK OF THE FUTURE

Despite the fact that the 400 kV network fulfils the high expectations with respect to economy and operating reliability, extensive investigations have been undertaken relating to the choice of the voltage for future installations. The reasons for this are to be found in the fact that the conditions are more assured than was the case in 1946 when the decision to adopt 400 kV was reached. Within 20 years it will be necessary to transport 45×10^9 kWh per annum, or 8 000–10 000 MW over an average distance of 500–600 miles. At the same time nuclear power stations or conventional steam power stations with outputs of 2 000 MW are being built in the vicinity of the load in South Sweden. The high-voltage technique has made appreciable advances during the past decade. The investigations related primarily to the alternatives, namely continued extension of the system at 400 kV, a change-over to 500 kV for existing and new lines, the superposition of a new 650 kV network and high-voltage direct current.

High-voltage direct current was unable to compete, on account of the costs for interconnection with the existing network, although the possibility of employing it in the future remains open however. A change-over from 400 to 500 kV a.c. was found to give a 3% reduction in transmission cost, whereas 650 kV would give a saving of 9%. These figures relate to a completely built-out network, and the conditions are found to be less favourable for the higher voltages during the period of expansion. The resultant gain from raising the voltage to 650 kV is so small, therefore, that it does not justify the subsequent complication of the network and the risks involved. It was consequently decided to continue to use 400 kV in the future.

The technical problems encountered in this network vary with the course of time. The load will be doubled in 10–12 years, which necessitates the construction of more and more lines with a constantly increasing loading capacity. The stability problems are rendered easier, the demands on insulation are lowered, whereas the short-circuit power rises. The specific Swedish problems thus come to resemble the problems in countries with a concentrated network more and more closely, although they never entirely lose their own distinctive character.

DISCUSSION ON
'PROGRESS IN PERMANENT-MAGNET MATERIALS'*

RUGBY SUB-CENTRE, 17TH FEBRUARY, 1960

Mr. L. Griffiths: The major commercial developments during the 12-year period reviewed in the paper have been the consolidation of the anisotropic aluminium-nickel alloys and the introduction of the columnar crystal-growth technique. As a result of these two developments, the $(BH)_{max}$ value has been raised from 4·5 to 7·5 MG-oersteds. Considering the previous improvements in permanent-magnet characteristics, this is undoubtedly a remarkable achievement.

These improvements are particularly noteworthy for their conformity with the progress predicted from the prior development. This is graphically illustrated by Fig. A, from which it will be noted that the plotted values derived mainly from test specimens agree quite well with the predicted rate of increase based on developments up to 1940.

The consistency of the rate of increase in $(BH)_{max}$ since the introduction of aluminium-nickel alloys in 1931 raises the question whether the maximum potentialities of these alloys have yet been reached. What are the author's views on this point?

From the user's standpoint, the aluminium-nickel alloys have gone a long way towards meeting size and cost requirements of designers, as Fig. B exemplifies. For very many present-day applications of Alcomax magnets, the magnet weight is less than ¼ lb. In such cases, casting and machining costs, rather than material cost, decide the price. On the other hand, the notably higher magnetic energy of Columax renders this materia

* GOULD, J. E.: Paper No. 3069 M, December, 1959 (see 106 A, p. 493).

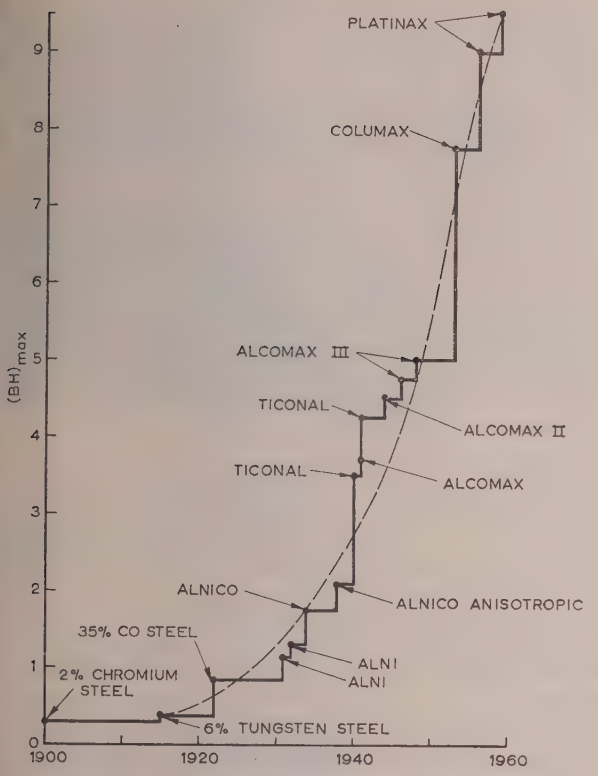


Fig. A.—Progressive developments in permanent magnets.
• Calculated.
--- Predicted.

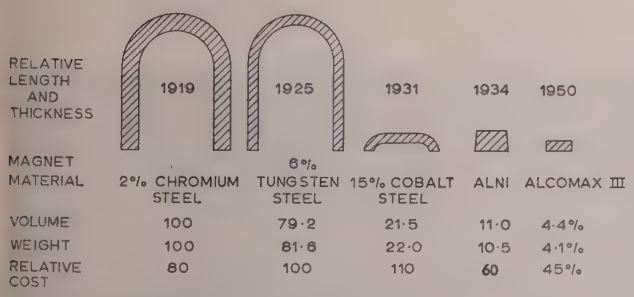


Fig. B.—Motor-cycle magneto magnets: comparative data.
Relative cost is based on pound sterling.

attractive for applications involving permanent magnets of 40 lb weight or even more. In these applications, still further improvements in the energy would be particularly advantageous in effecting size and weight reduction, even though cost may not be similarly affected. What is the author's view on the potentialities of Columax for these applications, for which purpose a simple annular magnet with a bore of about 4 in diameter would seem most suitable?

Mr. P. G. Ross: I shall confine my remarks to the application of permanent magnets to rotating electrical machines, in particular salient-pole a.c. generators. For certain applications the permanent-magnet alternator offers real advantages over its excited counterpart, yet the increase in the use of permanent magnets for machines of ratings from 5 to, say, 100 kVA has not been as rapid or widespread as might have been expected.

The new anisotropic nickel-aluminium-cobalt alloys with aligned and part-aligned grain structure offer great promise in view of their excellent magnetic properties. On salient-pole a.c. generators it is often convenient to use solid mild-steel pole shoes and to fix the magnets and the pole shoes by means of bolts which screw on to the spider. The magnets must then have slots or, more conveniently for the designer, cored holes. At the moment Columax and Ticonal GX can be produced only in a simple shape—basically cylindrical and with a length less than the diameter. This shape is not very useful as far as salient-pole a.c. machines are concerned. Is it likely that improvements in manufacturing techniques will result in materials with columnar structure becoming available in rectangular shapes with cored holes and without too great an increase in cost? The present technique would seem to rule this out.

Up to the present, designers have avoided using an Araldite type of glue for fixing the permanent magnets to the spider and the pole shoes to the magnets. Are the mechanical properties of the materials of the Alcomax family likely to improve sufficiently for this method of fixing to be used or could it in fact be employed at present?

Mr. K. F. Raby: Permanent magnets are rarely used in industrial machines for straightforward electro-mechanical energy conversion, except perhaps in the smallest sizes. They have found application, however, in some special-purpose machines where their potential advantages (long-term stability, independence of external supplies, elimination of slip-rings, etc.) are of particular value.

The lack of progress in the application of permanent magnets to conventional machines is due to two major disadvantages:

There is no convenient means of control of field strength, the rating of a permanent-magnet machine being determined more often by inherent regulation than by temperature rise.

The intractable mechanical properties of modern high-energy permanent-magnet materials do not make for freedom in design or economy in manufacture.

From a comparison of the published demagnetization curves, one should obtain, by a simple change from Alcomax III to Columax, in a machine which is correctly designed for maximum energy utilization with Alcomax III and not saturated in any part of the magnetic circuit, an increase of at least 10% in voltage or 20% in power output. We have recently tried this direct substitution on each of two different designs, but have not observed any appreciable improvement. Can the author suggest possible explanations for these disappointing results?

Mr. J. E. Gould (*in reply*): The graphic illustrations of permanent-magnet progress in Figs. A and B are of great interest. The limit in Fig. A has already been exceeded by the work of Luteijn and de Vos,[12] who have attained $(BH)_{max}$ values of over 11 MG-oersteds on laboratory single crystals. It is my opinion that this value is near the limit for the nickel-aluminium-cobalt alloys, since it is obtained by taking the alloy compositions of highest coercivity and using special techniques to produce the highest alignment in a composition which responds rather indifferently to the normal methods of field treatment. The technological objective should be to reach such values by processes which are feasible in production. Fig. B indicates how monetary inflation has been nullified by technical progress in this particular field, since equivalent magnets cost substantially less in 1950 than in 1934 or 1931. Crystal-oriented alloys such as Columax are particularly suitable for the production of large permanent-magnet castings, but not very suitable for the average small size mentioned by Mr. Griffiths. Magnet shape in Columax must be simple in the sense that the cross-section perpendicular to the axis of the aligned crystals must be of dimensions which are

large relative to the length of the axis of alignment. The smallest distance between mould surfaces should not be less than the magnet length.

Mr. Ross raises a similar point. Columax need not be cylindrical in cross-section, but the length should not exceed the smallest perpendicular distance between surfaces, including any cored holes. Exploration of other methods of producing crystal orientation is being pursued, but at present the only method is by a controlled freezing of the alloy from the polar surfaces. It is therefore essential to keep other surfaces at a minimum.

Both Mr. Ross and Mr. Raby refer to the relatively small use of permanent magnets in rotating electrical machines of above minimum size. I am not sufficiently in touch with the problems of this application to comment in detail, but there is an increasing use of permanent magnets for special generators and this use seems to be expanding more rapidly in the United States than in this country. The mechanical properties of the nickel-aluminium magnet alloys are poor compared with other ferrou alloys and tests always give a wide spread in properties. It i necessary to consider the details of each individual design t decide whether it is essential to hold the magnet material i compression. Most magnet manufacturers are reluctant t quote a tensile strength for these alloys because the grain struc ture and strength are very dependent on the precise size an shape of the casting. A centrifugal-force test on sample magnet is the more reliable approach.

Mr. Raby's example of a direct substitution of Alcomax III b Columax without appreciable improvement is surprising an needs fuller investigation. As can be seen from Fig. 1, Columa should be better for all working conditions, but the squarer-loo material is more critical in design if maximum benefit is to b obtained. It must also be remembered that the assumption o uniform B and H values throughout the magnet volume is some times a very rough approximation and that this could reduce th benefits of a direct substitution.

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The Institution of Electrical Engineer
Abstract No. 351
Feb. 196

THE ASWAN HYDRO-ELECTRIC SCHEME

By V. FURUSKOG, C.E., M.A.S.C.E., and GEOFFREY KENNEDY, M.A., M.I.C.E., M.I.Mech.E., Member.

(ABSTRACT *of a paper which was received by* THE INSTITUTION OF CIVIL ENGINEERS 24*th November*, 1959, *and was read at a joint meeting of that* INSTITUTION *and* THE INSTITUTION OF ELECTRICAL ENGINEERS 22*nd November*, 1960.)

The paper describes the 350 MW power station which has been built at Aswan in the southern region of the United Arab Republic. This project should not be confused with the Aswan High Dam project, which is being financed and built by the U.S.S.R. It is a scheme which has been designed to use the head across the existing dam at Aswan for generating electrical power. Because of seasonal fluctuations in the level of water in the reservoir upstream and in the river downstream of the dam, the amount of power is not constant and varies from a maximum of about 300 MW during seven and a half months of the year to about 50 MW in the last fortnight of July. These variations will be smoothed out when the High Dam has been built.

The wide fluctuation in the amount of power available meant that the scheme could only be justified if the cost of electricity was cheap enough to attract electrochemical or electrometallurgical industries which would be dependent upon cheap non-firm power. This was found practicable at Aswan, and the great bulk of power generated there is now being used for the production of artificial fertilizer at a factory which has been constructed near by. This factory will take the non-firm power, and the firm power will be transmitted downstream for supplying high-lift pumping stations in the Nile Valley.

Schemes for developing power in association with the existing dam at Aswan had been under consideration for many years, and the project finally selected utilized a depression in the river bank to the south-west of the existing dam. In this depressio has been built a new intake dam with the power station imme diately downstream of it. Downstream of the power statio there is a surge basin from which the water is led back into th river below the existing dam, by four tunnels each having a sectional area of 150 m^2. The general layout of the project i shown in Fig. 1.



Fig. 1.—Model of the Aswan area.
Power plant is in foreground.

The great bulk of the plant came from various Europea countries and from the United Kingdom and was delivered t the Mediterranean port of Alexandria. From there it wa shipped up the Nile by barge because this route could carr heavier and bulkier pieces more economically than was possibl over the single-track railway. On arrival at Aswan the barge

Mr. Furuskog is with Vattenbyggnadsbyrån, Stockholm. Mr. Kennedy is with Kennedy and Donkin. For his part in the design of the project and the co-ordination of the engineering services, Mr. Kennedy was awarded the Order of Merit, First Class, by President Nasser.

The paper was published in the *Proceedings of The Institution of Civil Engineers*, 1960, 17, p. 201. The discussion will be published by that Institution in or after April, 1961.



Fig. 2.—100-ton crane.

were off-loaded by a 100-ton crane spanning one of the locks associated with the existing dam, as shown in Fig. 2. A fleet of transport vehicles was provided on the site to move plant from the off-loading point to the various construction sites.

The variable head available at Aswan led to the choice of 65 000 hp Kaplan turbines—some of the largest in the world at the time they were ordered. The stainless-steel runners (Fig. 3) are 18 ft in diameter, and one could easily drive a London double-decker bus with a small car on top of it into the entrance of the steel spiral casings, which have a diameter of 23 ft 6 in. There are seven turbines of this type in the scheme located at centres of 73 ft and running at a speed of 100 r.p.m. These drive 47 000 kW 11 kV generators. Each generator is connected solidly to an 11/132 kV 51 MVA transformer, situated on the deck downstream of the power station immediately above the surge basin. The transformers are connected by overhead transmission lines run from the superstructure of the power house across the surge basin to the 132 kV outdoor switching station

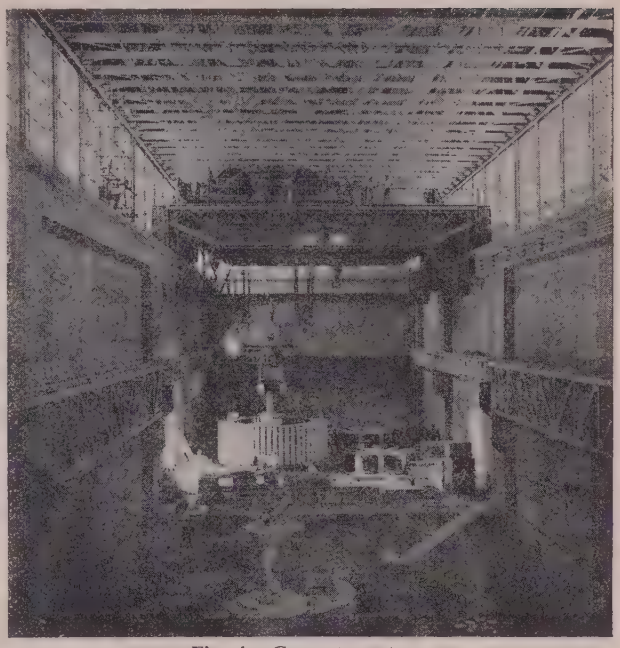


Fig. 4.—Generator rotor.

on the west bank. From this switching station, feeders are taken to the fertilizer factory, to irrigation pumping stations farther down the Nile, and to the site of the High Dam project for construction purposes. Space has been left for additional feeders in case they should be required in the future.

At the time the contracts for the main plant were placed, no single manufacturer was willing to accept an order for the total number of turbines or generators required, and orders for both turbines and generators were therefore split amongst different



Fig. 3.—Runner of Kaplan turbine.

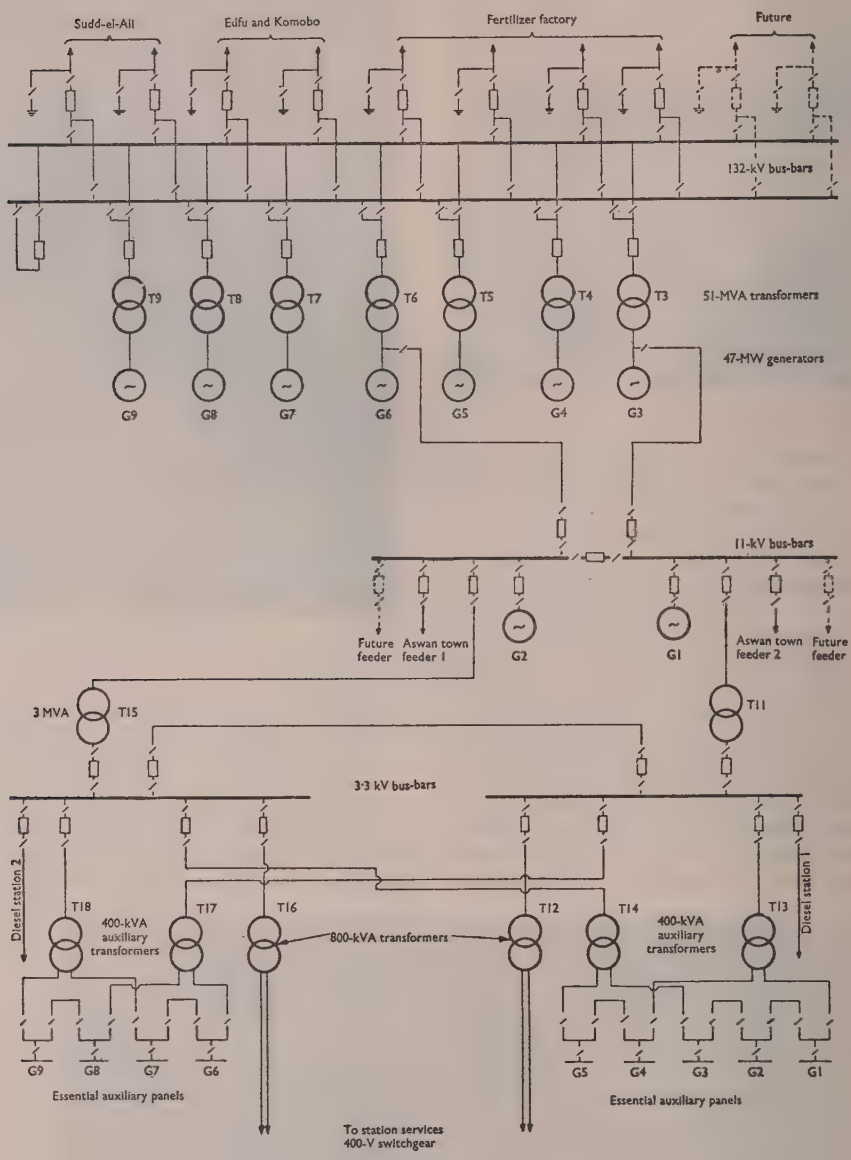


Fig. 5.—Main electrical connections.

manufacturers. This arose partly because of congestion in manufacturers' works and also because of the large dimensions of units of this type. To lift the generator rotors into position after they had been assembled on the turbine-house loading bay, the two 265-ton cranes in the turbine house were coupled together with a special lifting beam to lift the total weight of nearly 500 tons. A typical generator rotor is shown in Fig.4.

To supply power for auxiliaries, two house turbine-generators have been supplied which have a rating of 11 500 kW and are connected directly to the 11 kV indoor switchboard. This switchgear is alternatively supplied by direct connections from main generators Nos. 3 and 6. From this switchgear supplies are given to Aswan town and also to transformers stepping down to the 3·3 kV switchboards. As an alternative to the supply from the 11/3·3 kV transformers, the 3·3 kV switchboard is fed by a Diesel station having a capacity of 1 000 kW. From the 3·3 kV switchboards supplies are taken to the various 3·3 kV/415-volt transformer substations located around the site.

In addition to supplying the auxiliaries in the power station itself, the 415-volt switchboards also supply power to the colony, the water-filtration and ice-making plants and the various other services required on a site of this kind. A diagram of the main electrical connections is shown in Fig. 5.

Many difficulties were encountered during the construction of this great international scheme, but whether due to technical, climatic or political reasons, they were solved without affecting the construction programme. The successful completion of the project is a tribute to the happy and effective collaboration between the engineers of the Hydro-Electric Power Department in Cairo and their British and Swedish consulting engineers.

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PROPERTIES AND THEORY OF THE ELECTRIC ARC

A Review of Progress

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(1) INTRODUCTION

The electric arc was observed originally in the first years of the nineteenth century. Researches into the properties of the arc followed rapidly upon its discovery, and the early experiments culminated in the noteworthy measurements of Mrs. Ayrton[1] on the voltage/current characteristics of the carbon arc.

During the present century our experimental and theoretical knowledge of atomic structure and processes has been greatly enhanced. This knowledge, together with the considerable experimental results now available on general gaseous conduction, enables us to present a reasonably complete description of the structure and properties of the electric arc. However, our knowledge of the arc under complex conditions is not yet sufficiently developed, and the optimum engineering of arc equipment is still not possible. The growing importance of the thermonuclear and direct-power-generation problems underlines the necessity for further arc and gaseous-conduction research.

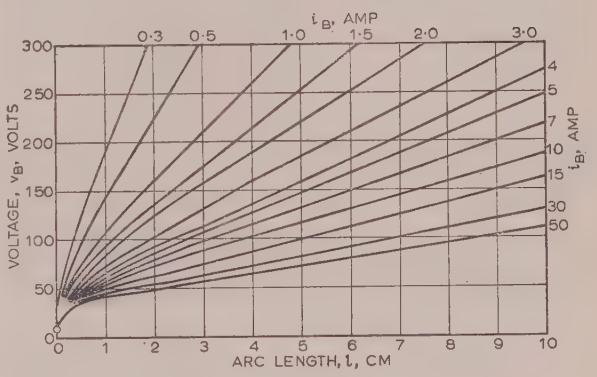


Fig. 1A.—Voltage/length characteristics of free-burning arc on copper electrodes (after Rieder[95]).

(2) ELEMENTARY ARC STRUCTURE AND PROPERTIES

The electric arc can be initiated by the separation of current-carrying contacts, the melting and vaporization of thin wires, transition from a glow discharge, or transition and follow-through of an impulse or high-frequency spark breakdown.

For all arcs the conducting gas between the electrodes has a high temperature (>4000°K) and high luminosity. The conducting arc column acts as a normal electrical conductor in the presence of a magnetic field, although anomalous electromagnetic effects have been observed at the cathode. Because of its gaseous nature, the arc is easily influenced by gas flow. However, the spatial stability of arcs is greatly dependent on the nature of the cathode material. Thus with typically refractory cathodes, e.g. carbon, molybdenum and tungsten, the cathode temperature is high and the arc is relatively stable. With low-melting-point cathodes, e.g. copper and mercury, the cathode termination is a highly mobile and concentrated spot which moves constantly over the cathode surface in an irregular fashion. These visual differences are the result of different cathode mechanisms and lead to the classification of arcs into two main types—refractory and non-refractory or cold-cathode arcs. Both arc types, however, have essentially the same column properties.

Considerable information on arc structure and properties can be obtained by the determination of voltage/current and voltage/length characteristics. These simple experiments are, however, beset with numerous practical difficulties, and great care is required before reproducible characteristics are obtained. Figs. 1A and 1B are examples of recent work on the steady-state characteristics, from which some important generalizations can be made. Thus at low currents the voltage falls with increasing current (negative characteristic), but at higher currents the voltage tends to rise slowly (positive characteristic). The voltage characteristics indicate that a finite voltage still exists across the arc at zero length. The Figures indicate further that for gap lengths greater than 1–2mm the potential distribution

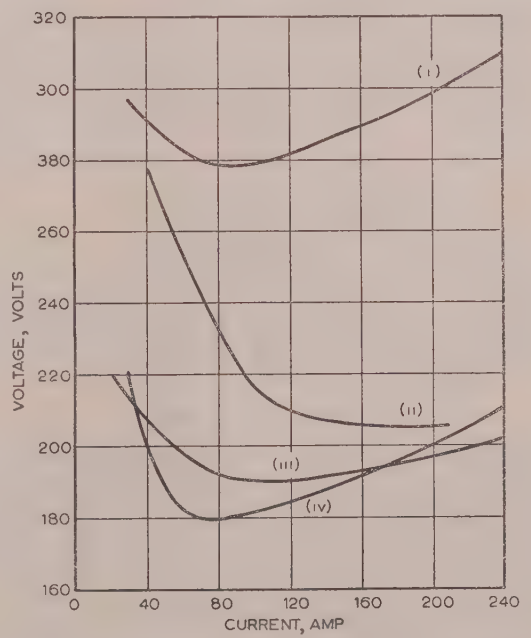


Fig. 1B.—Voltage/current characteristics of water-stabilized high-current arc (after Burhorn and Maecker[32]).

(i) 11·4mm diameter, 26mm long.
(ii) 2·3mm diameter, 61mm long.
(iii) 11·4mm diameter, 16mm long.
(iv) 1·4mm diameter, 6·5mm long.

in the arc is uniform. In this condition the arc column is usually cylindrically symmetric. We thus recognize a potential distribution in the arc as shown by Fig. 2(*a*) with the existence of three main arc regions, namely a positive column extending over the major portion of the arc path and having a constant

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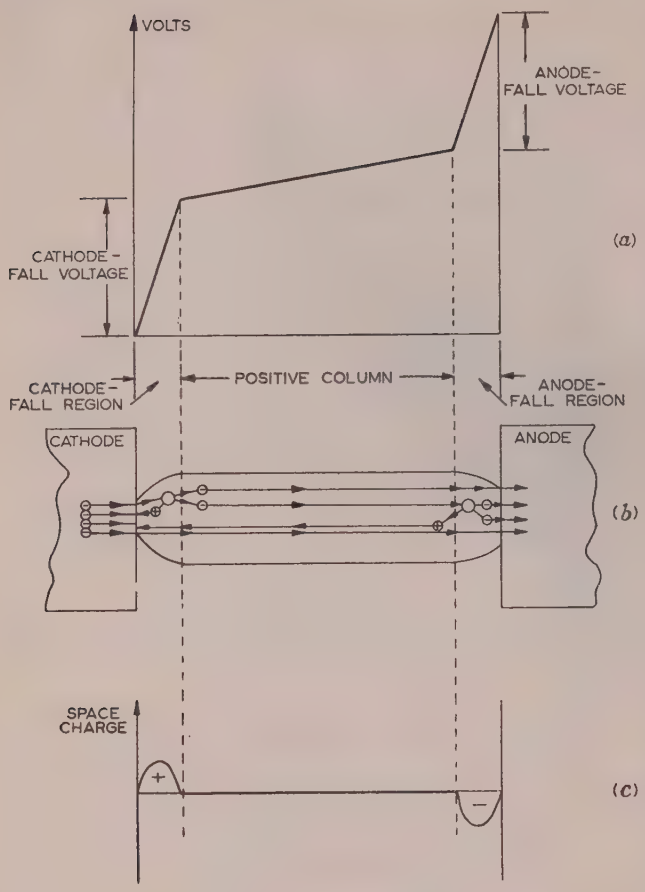


Fig. 2.—Distributions in arc.
(*a*) Potential.
(*b*) Current.
(*c*) Space charge.

field strength, a cathode-fall region close to the cathode (about 10^{-4}cm) and supporting a voltage approximately 10 volts, and an anode fall region of similar size and voltage drop.

(2.1) The Positive Column

Since experiment shows that the field strength is constant for a cylindrically symmetric column, we note from Poisson's law that the net space-charge is zero. This indicates that the concentration of positive, n_+, and negative, n_-, charges, must be equal. The positive column therefore satisfies the definition of a plasma, and this is true in general for all column configurations. The current flowing through the column will have two components, an electron current J_- and a positive-ion current J_+. The total current density is

$$J = J_- + J_+ = e(n_- v_- + n_+ v_+) = ne(v_- + v_+) \quad (1)$$

where v_- and v_+ are the drift velocities produced by the field. The drift of the charged particles is impeded by collisions with neutral and other charge carriers. This represents a resistive phenomenon. Since $v_- \gg v_+$, the total current is carried predominantly by electrons. Thus

$$J \simeq J_- = n_- e v_- = n_- e \mu E = \sigma E \quad . \quad . \quad . \quad (2)$$

where μ is the electron mobility and σ the electrical conductivity; σ is a complex function of the gas composition and temperature, and is related to J_- through the energy conditions in the plasma. Because of this the functional relationship in eqn. (2) is very different from the relationship when applied to metallic conduction.

(2.2) The Cathode-Fall Region

To satisfy the continuity condition the current flowing through the positive column must also make the transit from gas to metal at both electrodes. In the cathode region, therefore, conditions must exist which allow this transition and also in most cases produce a self-maintaining phenomenon. For refractory cathodes it is well established that the mechanism is one of thermionic emission. Wehrli's[2] experiments clearly show a continuous and controllable transition from a glow to an arc state dependent upon cathode temperature (see Fig. 3). An

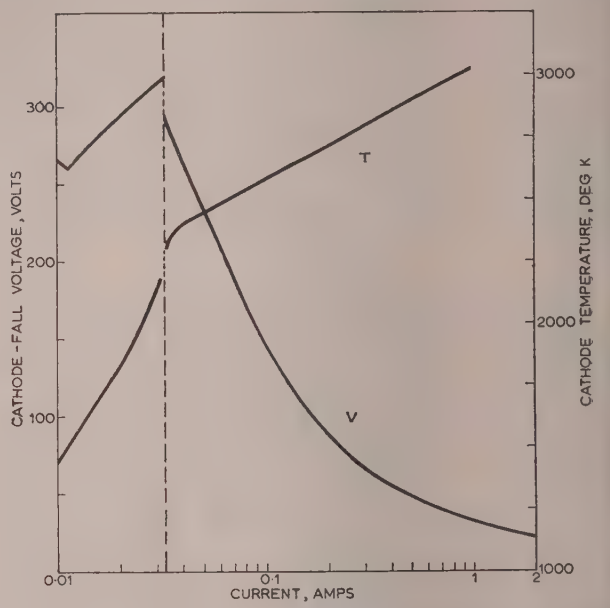


Fig. 3.—Variation of cathode-fall voltage and cathode temperature during thermionic glow-to-arc transition (after Wehrli[2]).

analysis based upon thermal factors has been given by von Engel and Steenbeck[3] and shows good agreement between theoretical and experimental results. The mechanism of the cold cathode is by no means as fully understood, and many explanations have been proposed. The most widely held view is that cathodic electron emission is induced by the presence of very high electric fields. The theories and properties of the cathode region are more fully discussed in Section 5.

(2.3) The Anode-Fall Region

Positive-ion emission from the anode can be neglected for most arc conditions. In this region current continuity is therefore achieved by the total current being fed into the anode by electrons, which necessitates the production of extra electrons in the anode region. The theories of this mechanism are discussed later.

(2.4) Definition of the Arc

Considerable discussion has taken place for many years on the appropriate definition of the arc. The arc not only has a complex structure of its own, but it has also been shown recently,[4]

for example, that composite glow-arc discharges can exist. For these reasons a suitable definition of a fully developed arc may be given as 'a steady-state discharge having a positive column in thermal equilibrium and a cathode fall of small voltage and high current density'. By defining the arc thus we exclude transient discharge forms such as the spark, which at high currents has characteristics approximating to those normally associated with the arc discharge.

(3) THEORY OF ELECTRICAL CONDUCTION IN GASES

A more detailed understanding of arc structure and properties requires a study of the general theory of electrical conduction in gases. This theory, which relates phenomena associated with electrical conduction, electromagnetics, gas kinetics and thermodynamics, can be stated here only in concentrated form. Further descriptions can be found in the classic treatise of Chapman and Cowling[5] and in the publications of other workers.[6,7]

(3.1) Defining Relations for a Gas Mixture

Consider a gas mixture comprising a number of species with species s having a particle mass m_s, concentration n_s, velocities $\boldsymbol{c}_s$ and mean velocity $\bar{\boldsymbol{c}}_s = \boldsymbol{v}_s$ and possible charge multiplicity Z_s; then a number of defining relations exist for the mixture, as follows:

Total concentration: $$n = \Sigma n_s \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Total mass density: $$\rho = \Sigma n_s m_s = \Sigma \rho_s \quad . \quad . \quad (4)$$

Velocity of centre of gravity: $$\boldsymbol{v}_0 = \Sigma \rho_s \boldsymbol{v}_s / \rho \quad . \quad . \quad . \quad (5)$$

Net space charge: $$\rho_e = \Sigma n_s Z_s e_s = \Sigma \rho_{es} \quad . \quad (6)$$

Total current density: $$\boldsymbol{J} = \Sigma \rho_{es} \boldsymbol{v}_s \quad . \quad . \quad . \quad . \quad (7)$$

If the velocities are referred to the centre of gravity such that $\bar{\boldsymbol{c}}'_s = \boldsymbol{v}_s - \boldsymbol{v}_0$ we then note that, for example, the current density consists of a mass convection-flow component $(\rho_e \boldsymbol{v}_0)$ and a purely conductive current $\Sigma \rho_{es} \bar{\boldsymbol{c}}'_s$.

(3.2) The Conservation Equations

The equations of conservation of mass, momentum and energy of the gas mixture are readily obtainable from the general equation of change based on Boltzmann's equation for the velocity distribution in any one species.

Conservation of mass.—If $\Delta \rho_s$ is the rate of generation of mass density of species s, then, for conservation, $\Sigma \Delta \rho_s = 0$. Thus we obtain for one component and the total mixture respectively,

$$\frac{\partial \rho}{\partial t} + \nabla . (\rho_s \boldsymbol{v}_s) = \Delta \rho_s \quad . \quad . \quad . \quad . \quad (8)$$

$$\frac{\partial \rho}{\partial t} + \nabla . (\rho \boldsymbol{v}_0) = 0 \quad . \quad . \quad . \quad . \quad . \quad (9)$$

Conservation of momentum (the equation of motion).—In this case, if $\boldsymbol{P}_s$ is the rate of change of momentum of species s produced by collisions with other species then $\boldsymbol{P}_s = \Sigma \boldsymbol{P}_{sr}$, $\boldsymbol{P}_{sr} = \boldsymbol{P}_{rs}$ and $\Sigma \boldsymbol{P}_s = 0$. The equations of motion of one component and the total gas mixture are

$$\frac{\partial}{\partial t}(\rho_s \boldsymbol{v}_s) + \nabla . (\rho \bar{c}_s \bar{c}_s) - \rho_s \boldsymbol{F}_s = \boldsymbol{P}_s \quad . \quad . \quad (10)$$

$$\rho \frac{D \boldsymbol{v}_0}{Dt} + \nabla p - \Sigma \rho_s \boldsymbol{F}_s = 0 \quad . \quad . \quad . \quad (11)$$

where $\boldsymbol{F}_s$ is the external force per unit mass exerted on the species and p is the total pressure.

Conservation of energy.—The energy equations are particularly important for arc studies. If the average total kinetic and internal energy of the gas mixture per unit volume is $\bar{\epsilon}$, the equation for the mixture is

$$\frac{\partial \bar{\epsilon}}{\partial t} + \nabla . (\boldsymbol{q} + h \boldsymbol{v}_0) - \Sigma \rho_s \boldsymbol{F}_s . \boldsymbol{v}_s = 0 \quad . \quad . \quad (12)$$

where $h = p + \bar{\epsilon}$ is the enthalpy per unit volume and $\boldsymbol{q}$ is a thermal flux vector given by $\boldsymbol{q} = -\Sigma K_s \nabla T$; K_s being the thermal conductivity and T the temperature of species s. With electric, magnetic and gravitational forces of potentials V, A and Φ respectively, the equation becomes

$$\frac{\partial \bar{\epsilon}}{\partial t} + V \frac{\partial \rho_e}{\partial t} + \Phi \frac{\partial \rho}{\partial t} + \nabla . [\boldsymbol{q} + \boldsymbol{v}_0 (h + \rho \Phi) + J V] = 0 \quad (13)$$

Thus if there is an accumulation of both charged and uncharged particles in the volume, the rate of energy increase is the sum of the increases in internal, gravitational and electric-potential energies. The net increase is the result of the difference between the input of energy $\nabla . (JV)$ and the losses due to the net outflow of thermally conducted energy and outflow of particles with enthalpy and gravitational potential energy.

(3.3) Current Density Equations

Neglecting the current component due to convective flow we have, from eqn. (7), the conduction current given by

$$\boldsymbol{J} = \Sigma \rho_{es} \bar{\boldsymbol{c}}'_s \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

The velocities $\bar{\boldsymbol{c}}'_s$ are not easily determinable for complex gas mixtures, but in the special case of a 2-component mixture $\boldsymbol{J}$ can be shown to be directly proportional to the velocity of diffusion of one component into the other—a velocity well known from gas theory. The binary gas mixture adequately represents the following two important limiting cases:

Fully Ionized Gas.—

$$\boldsymbol{J} = \mu_- [n_- e (\boldsymbol{E} + \boldsymbol{v}_- \times \boldsymbol{B}) + \nabla \Phi] \quad . \quad . \quad (15)$$

where $\mu_- = eD_{-+}/kT$ is the mobility in a binary mixture and D_{-+} is the coefficient of diffusion.

Weakly Ionized Gas.—In this case the two current components are taken as diffusing separately into the un-ionized gas, so that

$$\boldsymbol{J}_- = \mu_- [n_- e (\boldsymbol{E} + \boldsymbol{v}_- \times \boldsymbol{B}) + \nabla p_-] \quad . \quad . \quad . \quad (16)$$

$$\boldsymbol{J}_+ = \mu_+ \left[n_+ e (\boldsymbol{E} + \boldsymbol{v}_+ \times \boldsymbol{B}) - p \nabla \left(\frac{p_+}{p} \right) \right] \quad . \quad (17)$$

where $\mu_- = eD_{-a}/kT$ and $\mu_+ = eD_{+a}/kT$; D_{-a} and D_{+a} are the coefficients of diffusion into the neutral gas of the electrons and ions respectively. With constant total pressure and uniform conditions and with $\boldsymbol{B} = 0$ we obtain the well-known equations

$$\boldsymbol{J}_- = n_- e \mu_- \boldsymbol{E} + e D_{-a} \nabla n_- \quad . \quad . \quad . \quad (18)$$

$$\boldsymbol{J}_+ = n_+ e \mu_+ \boldsymbol{E} - e D_{+a} \nabla n_+ \quad . \quad . \quad . \quad (19)$$

With the further assumption of no concentration gradient we obtain the simple equation (2).

The transient current-density equations can easily be obtained from the equations of motion of any one gas component [eqn. (10)]. With $\boldsymbol{J} \simeq \boldsymbol{J}_-$ this gives

$$\frac{m_-}{n_- e^2} \frac{\partial \boldsymbol{J}}{\partial t} + \eta \boldsymbol{J} = (\boldsymbol{E} + \boldsymbol{v}_0 \times \boldsymbol{B}) - \frac{\boldsymbol{J} \times \boldsymbol{B}}{n_- e} + \frac{\nabla p_-}{n_- e} \quad (20)$$

where the resistivity is $\eta = P_- / n_- e J$ and P_- is the rate of change of momentum of the electrons due to collisions with atoms and ions. Thus η represents a true Joule heating.

(3.4) Equations of Current Continuity

From the conservation of mass equation (8) one can obtain

$$\frac{\partial \rho_{e-}}{\partial t} + \nabla . \boldsymbol{J}_- = \Delta\rho_{e-} \quad . \quad . \quad . \quad . \quad (21)$$

$$\frac{\partial \rho_{e+}}{\partial t} + \nabla . \boldsymbol{J}_+ = \Delta\rho_{e+} \quad . \quad . \quad . \quad . \quad (22)$$

where $(1/e)\Delta\rho_e$ is the number of charged particles of one species produced per second per unit volume. Excluding preferential generation or loss of one charge type, $\Delta\rho_{e-} = -\Delta\rho_{e+}$. With ionization and recombination at rates λ_i and λ_r,

$$\Delta\rho_{e+} = -\Delta\rho_{e-} = e(\lambda_i - \lambda_r)$$

Adding eqns. (21) and (22) gives the continuity equation

$$\frac{\partial \rho_e}{\partial t} + \nabla . \boldsymbol{J} = 0 \quad . \quad . \quad . \quad . \quad . \quad (23)$$

To complete the electrical description of the conductive gas we require Maxwell's equations and the field-potential relationship

$$\left.\begin{aligned} \nabla . \boldsymbol{D} &= \rho_e \\ \nabla \times \boldsymbol{E} + \frac{\partial \boldsymbol{B}}{\partial t} &= 0 \\ \nabla . \boldsymbol{B} &= 0 \\ \nabla \times \boldsymbol{H} - \frac{\partial \boldsymbol{D}}{\partial t} &= \boldsymbol{J} \\ \boldsymbol{E} &= -\nabla V \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (24)$$

The equations given in this Section are adequate for many analyses of gaseous arc phenomena, although a more complete description requires the consideration of further thermo-dynamic and other concepts.

(3.5) The Steady-State Thermal Positive Column

As an example of the use of the preceding equations consider the special case of an arc positive column in a steady state and in thermal equilibrium. Then for a mixture of ions, electrons and atoms,

$$\left.\begin{aligned} \rho_- \boldsymbol{F}_- &= -n_- e(\boldsymbol{E} + \boldsymbol{v}_- \times \boldsymbol{B}) - \rho_- \nabla\Phi \\ \rho_+ \boldsymbol{F}_+ &= Zn_+ e(\boldsymbol{E} + \boldsymbol{v}_+ \times \boldsymbol{B}) - \rho_+ \nabla\Phi \\ \rho_a \boldsymbol{F}_a &= \qquad\qquad\qquad - \rho_a \nabla\Phi \end{aligned}\right\} \quad . \quad (25)$$

The pertinent column equations then become:
from eqn. (11)

$$\nabla p - \rho_e \boldsymbol{E} - \boldsymbol{J} \times \boldsymbol{B} + \rho \nabla\Phi = 0 \quad . \quad . \quad (26)$$

from eqn. (12)

$$\nabla . [\boldsymbol{q} + \boldsymbol{v}_0(h + \rho\Phi) + J\boldsymbol{V}] = 0 \quad . \quad . \quad . \quad (27)$$

from eqn. (16)

$$\boldsymbol{J} \simeq \boldsymbol{J}_- = \mu_- [n_- e(\boldsymbol{E} + \boldsymbol{v}_- \times \boldsymbol{B}) + \nabla p_-] \quad . \quad . \quad (28)$$

Eqn. (26) becomes for a plasma ($\rho_e = 0$) and $\nabla\Phi = 0$ the well-known self-pinch equation for high-current discharges, but even in this form the equations are not easily solved rigorously. However, if ρ_e, $\nabla\Phi$, $\boldsymbol{v}_0$ and ∇n are all zero, the equations are simply

$$\boldsymbol{J} . \boldsymbol{E} = \nabla . (-K\nabla T) \quad . \quad . \quad . \quad . \quad . \quad (29)$$

$$\boldsymbol{J} = \sigma \boldsymbol{E} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

giving

$$\sigma E^2 = \nabla . (-K\nabla T) \quad . \quad . \quad . \quad . \quad . \quad (31)$$

Since K and σ can be determined as functions of temperature, eqns. (30) and (31), together with the equations $\nabla . \boldsymbol{J} = 0$ and $\nabla . \boldsymbol{E} = 0$, allow a complete determination of the column properties of this arc. With a given temperature boundary condition and electrode configuration, the Laplacian field for a given applied voltage can be determined ($\rho_e = 0$). Now

$$\nabla . \boldsymbol{J} = 0 = \nabla . (\sigma \boldsymbol{E}) = \boldsymbol{E} . \nabla\sigma + \sigma \nabla . \boldsymbol{E} = \boldsymbol{E} . \nabla\sigma. \quad (32)$$

so that the gradient of electrical conductivity and hence of temperature must be orthogonal with $\boldsymbol{E}$. We visualize, then, a current flow and isothermal distribution coincident with the field distribution. The temperature distribution may be found through eqn. (31) and the distribution of current density from eqn. (30), and by integration the total current is determined. In this manner we can determine the voltage/current characteristic and temperature distribution of the arc. More correctly, the arc column is only quasi-neutral and the small net space-charges produce field effects which destroy the simple orthogonal relation between ∇T and $\boldsymbol{E}$. The large space-charges in the electrode-fall regions will modify the effective electrode configuration; nevertheless the electric field is quite often closely Laplacian. For example, with a small separation between spherical electrodes, the arc column has a typical dipole field appearance. With large separations the column appears roughly cylindrical, mainly because the majority of the current flows along the central portion of the field where both $\boldsymbol{E}$ and σ are greatest.

With the theory given in this Section it is now possible to study the finer structure of the arc.

(4) THE POSITIVE COLUMN

Investigations of the arc column under diverse conditions have yielded considerable data on the electron and gas temperatures. The techniques of measurement and results have been reviewed by Edels[8] and Lochte-Holtgreven.[9] In general, arc-column temperatures extend upwards from 5000°K, and

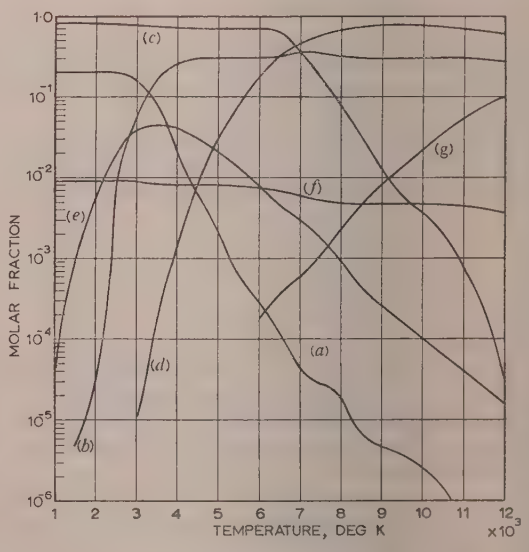


Fig. 4.—Variation of composition of air with temperature (after Stupochenko[10]).

Components as particle fraction of total gas composition (molar fraction).

(*a*) Oxygen molecules, O_2.
(*b*) Oxygen atoms, O.
(*c*) Nitrogen molecules, N_2.
(*d*) Nitrogen atoms, N.
(*e*) Nitric oxide.
(*f*) Argon.
(*g*) Electrons.

the evidence is that thermal equlibrium is closely approached; the electron and gas temperatures are thus the same and the analysis given in Section 3.5 is applicable. Importance must therefore be attached to the accurate determination of the coefficients of electrical and thermal conductivity, in the determination of which account must be taken of variation in gas composition with temperature due to dissociation and ionization.

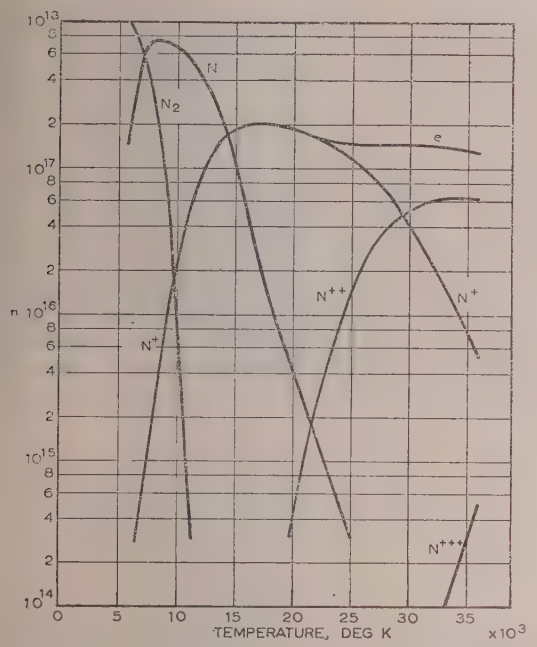


Fig. 5.—Variation of composition of nitrogen with temperature (after Busz and Finkelnburg[11]).

Pressure = Atmospheric.
n = Particle concentration/cm³.

Figs. 4 and 5 show the variation in the composition of air and nitrogen with temperature as given by Stupochenko[10] and Busz and Finkelnburg[11] respectively.

(4.1) Coefficient of Thermal Conductivity

The thermally conducted energy loss in a gas as represented by the thermal flux vector [eqn. (12)] must be taken to be the summation, not only of the classical thermal loss of ions, electrons and atoms, but also of the heat losses represented by the loss by diffusion of dissociation and ionization energy. The development of this generalization can be seen in the work of Rompe and Schulz,[12] Mannkopff[13] and Höcker and Finkelnburg.[14] Calculations by King[15] give the partial and total coefficients for nitrogen as shown in Fig. 6. The total coefficients for a mixture of 70% air and 30% carbon as given by Wienecke[16] and for hydrogen by King (private communication) are shown in Fig. 7. The sharp maxima in the curves due to the dissociation and ionization components are to be noted. In monatomic gases the function is simplified by the absence of the dissociation peak.

(4.2) Coefficient of Electrical Conductivity

The electrical conductivity, σ, is given by eqn. (2) as

$$\sigma = n_- e \mu_- \simeq \frac{0{\cdot}815 n_- e^2}{\sqrt{(3kTm)}} \frac{1}{\Sigma n_s Q_e^s} \quad . \quad . \quad (33)$$

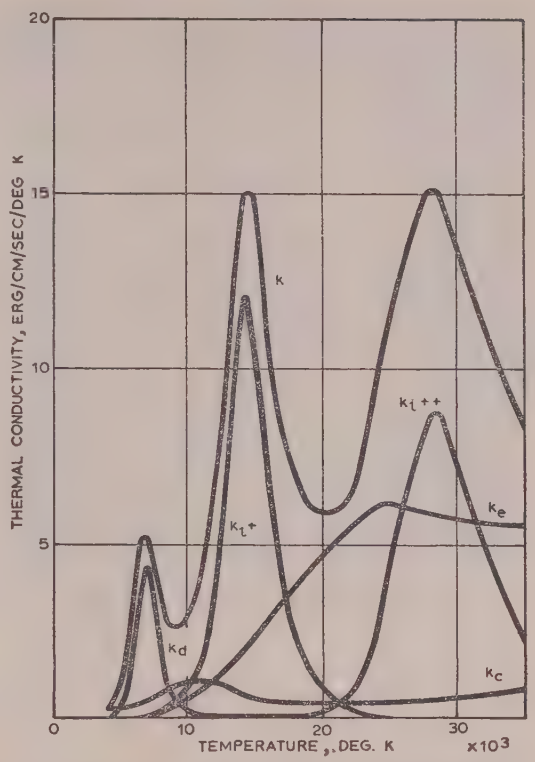


Fig. 6.—Variation with temperature of thermal-conductivity components of nitrogen gas components (after King[15]).

k Total conductivity.
k_d Dissociation component.
k_{i+} Single ionization component.
k_{i++} Double ionization component.
k_e Electron component.
k_c Classical component.

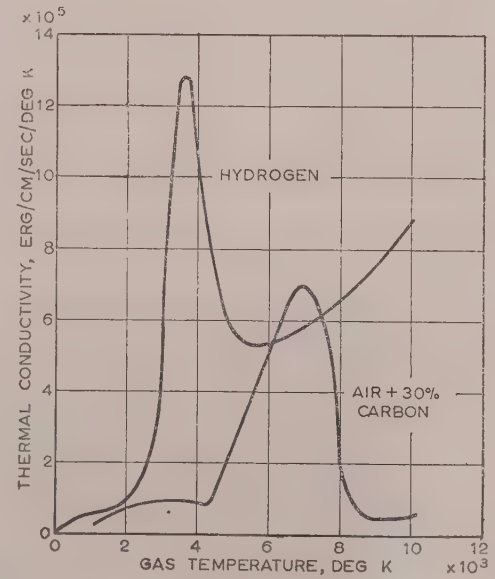


Fig. 7.—Variation with temperature of total thermal conductivity of hydrogen and of air with 30% carbon mixture.

where Q_e^s is the cross-section for collision between electrons and particles of species s and is obtained from calculated or measured data. The electron concentration can be determined as a function of temperature by using the Saha equation,[8,9] i.e.

$$\frac{n_+ n_-}{n_a} = \frac{n_-^2}{n_a} = \frac{U_+}{U_a} 2 \frac{(2\pi mkT)^{3/2}}{h^3} \exp\left(\frac{-eV_i}{kT}\right) \quad . \quad (34)$$

where U_+ and U_a are the partition functions of the ion and neutral atom respectively.

In gas mixtures the effective ionization potential, V_i, changes as the gas composition changes with temperature. All parameters in eqn. (33) can be expressed ultimately as functions of temperature and yield σ-functions, as shown in Fig. 8. The curve for argon is given by Olsen,[17] and that for nitrogen by King.[15]

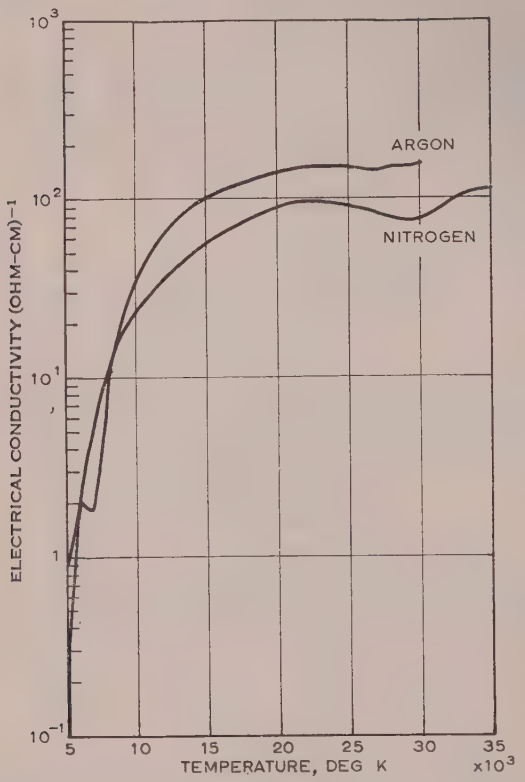


Fig. 8.—Variation with temperature of electrical conductivity of argon and nitrogen.

(4.3) Determination of the Temperature Distribution

In the steady state and for thermal equilibrium the temperature distribution is determined essentially by solution of the energy-balance equation (27), or, more correctly in an extended form, taking into account radiation $S(T)$ and convection losses $C(T)$. Since, particularly for molecular gases, the K-function is irregular and the functions $S(T)$ and $C(T)$ are highly complex, an analytic solution for the temperature distribution is impossible, although computer methods enable special solutions to be obtained.

(4.3.1) The Cylindrically Symmetric Column.

There is a long history of investigation of the temperature-distribution problem relating particularly to the special case of cylindrical symmetry. In general, the convection terms have been neglected. For monatomic gases, where reasonable approximations can be made to K and $S(T)$, an analytic solution becomes possible. In this case the energy-balance equation becomes the Elenbaas–Heller equation

$$\sigma E^2 = -\frac{1}{r}\frac{d}{dr}\left(Kr\frac{dT}{dr}\right) + S(T) \quad . \quad . \quad . \quad (35)$$

By assuming for $S(T)$ an exponential function such as $S(T) \propto (1/T) \exp(-eV_i/kT)$, the equation can be solved when the boundary conditions T_R at a radius R and $dT/dr = 0$ at $r = 0$ are given and E is constant. Calculations of this nature have been given in the literature;[18–22] assumptions of the form $K =$ constant and $K = K_0 T^\alpha$ were made, and the calculated distributions are in reasonable agreement with experiment.

For molecular gases such as nitrogen or gas mixtures, e.g. air, an analytic solution of eqn. (35) has not been found. However, radiation losses become negligible for many arcs in these gases as shown by Pelzer[23] for the carbon arc. In this case the temperature distributions may be determined by calculation using the exact K-curves. Mannkopff[13] carried out the calculations for the carbon arc using an iterative method, and his work was further developed by Maecker.[24] More recently King[15] has determined numerically the distributions for the nitrogen arc at different currents, and his results are shown in Fig. 9.

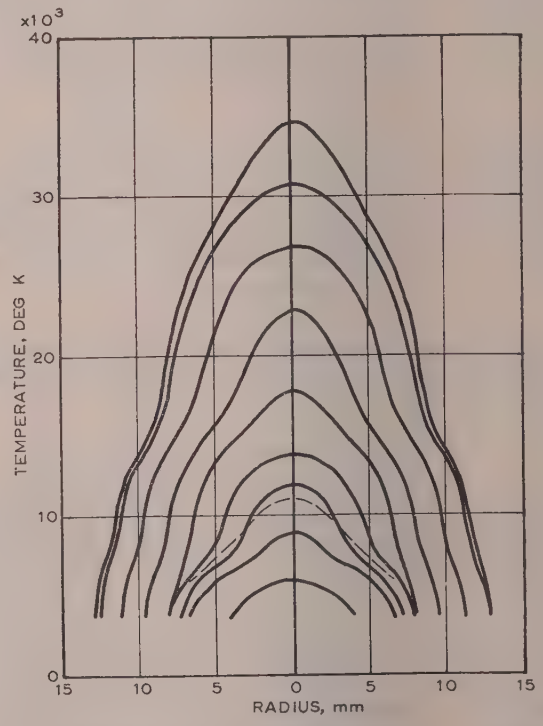


Fig. 9.—Radial temperature distribution of nitrogen arc (after King).
———— Theoretical (nitrogen).
— — — Experimental (air).

The development of an arc core due to dissociation and the increase of core temperature with current are shown. The calculations can be eased, however,[25,26] by using a function $S = \int K dt$, and since the σ, S function can be linearized without undue error, an analytic solution is possible.[27] The solution gives a zero-order Bessel-function distribution for S in the electrically conductive region, and a logarithmic distribution in

the outer regions where the electrical input is zero. Goldenberg[28] has developed further accuracy in the method by a step-by-step linearization of the S-function. The Bessel and logarithmic functions show that such arcs will always have distribution with a flat top and steep gradient in the outer regions. A measured N_2 distribution due to Burhorn[29] is given in Fig. 10.

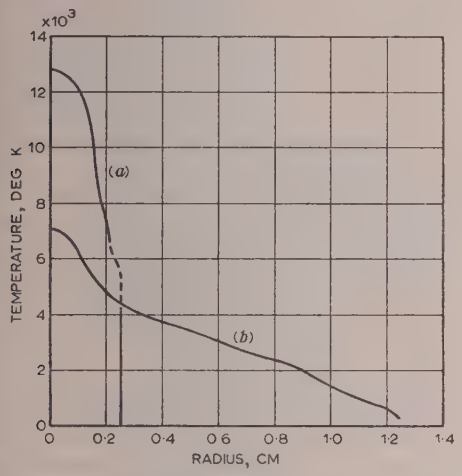


Fig. 10.—Measured radial temperature distributions.
(*a*) Wall-stabilized 100 amp nitrogen arc.
(*b*) Free-burning convection-stabilized 10 amp carbon arc.

(4.4) Types of Stabilized Arc Column

(4.4.1) Wall Stabilized.

As noted in the previous Section, when a cylindrically symmetric arc is limited by a fixed temperature boundary (T_R, R) and the loss process is predominantly by thermal conduction, the whole discharge is determined for a given current I and the arc is said to be wall stabilized. It follows that for fixed wall conditions the voltage/current characteristic can be determined analytically, and Maecker[27] gives an example of this. If we consider the current and wall radius as independent variables, then for many arcs the field strength, E, is determined almost entirely by R (thus by $E \alpha 1/R$), and the axial temperature, T_0, increases with the input power per unit length, EI. With forced cooling the effective wall radius decreases, so that, for a given current, EI and T_0 increase. This explains the apparent anomaly of increased temperature with enhanced cooling. The theory of wall stabilization is, of course, independent of the mode of production, material or shape of the fixed temperature wall. Such a boundary can be obtained with bored copper discs, as in the Gerdian arc or multiple Gerdian arc,[30] or with a gas or liquid vortex flow.[31, 32]

(4.4.2) Convection Stabilized.

Theory shows that in the wall-stabilized arc the discharge fills the major portion of the tube, and that for large tube diameters the arc can be wall stabilized only if very high currents and arc temperatures are produced. However, the large tube is essentially the condition of free burning, and it is well known that free-burning arcs are satisfactorily stabilized at low currents. Stabilization in this case is produced by convective gas flow. The interferogram of Fig. 11 is typical of a low-current arc and shows that, although the electrically conductive region is only 0·2mm in radius, the temperature falls to the ambient value only after 16mm. It is in this large external region where



Fig. 11.—Interferogram of 2 amp arc in hydrogen between 4 mm-diameter tungsten electrodes.
Obtained by K. R. Hearne and G. Howarth in this Department.

convection is important. The energy equation (27) for the steady state becomes, in a form suitable for convection studies,

$$\sigma E^2 = \nabla \cdot (-K \nabla T) + \rho v_0 \cdot (C_p \nabla T + \nabla \Phi) \quad . \quad . \quad (36)$$

where C_p is the specific heat at constant pressure. The addition of the convective term $\rho v_0 \cdot (C_p \nabla T + \nabla \Phi)$ makes it possible for arc stabilization to occur without the maintenance of thermal conduction to the wall boundaries. Thus in the outer regions of a cylindrically symmetric arc the energy flow is constant and equal to the total electrical input, but the sharing of the losses changes as the radius increases. Ultimately, before the wall boundaries are reached, the convective term predominates and the thermal conduction becomes negligible. The convecting gas flow acts effectively as a boundary wall and the arc is convection stabilized. In the electrically conductive region convection is not so important and the Elenbaas–Heller equation may be used.

Eqn. (36) shows that energy is transported by mass flow only when the flow has a component in the direction of the temperature or gravity gradient. In a vertical arc after a steady velocity has been produced by the balance between the forces of gravity and viscosity, the upward-moving gas flows into the lower arc portions, thus cooling this region. When leaving the upper arc region, however, the flow heats the arc, for the flow is against the temperature gradient. Thus convection tends to make a vertical arc broader at the top. With a horizontal arc a similar process occurs, the flow cooling the lower arc section and heating the upper section. In this case also, convection produces the arc bowing. An interesting analysis of this effect has been made by Weizel and Rompe.[33] Suits and Poritsky[34] have analysed the vertical convective arc, and, by analogy with the convective loss from a heated solid cylinder, have deduced relationships between the arc's electrical characteristics. Experimental and theoretical work on the convection of the high-pressure mercury discharge has been carried out by Elenbass,[35] while experimental studies of the flow have been made by Kenty,[36] Hagenah[37] and Wienecke.[38] The temperature distribution normally obtained for convective (free-burning) arcs is, as expected, very different in the outer regions of the discharge, as shown in Fig. 10.

(4.4.3) **Electrode Stabilized.**

When the electrode separation is small and the electrode mass is large, it is possible for the arc to be dominated and stabilized by the energy loss to the electrodes. In this case the electric field and current distribution may be symmetric about the mid-plane of the electrode system. Weizel and Rompe[33] and Schmitz[39] have analysed this form of stabilization.

(4.5) The Minimum Principle

Calculations on the positive column may be eased by utilizing a channel model which assumes the column to be an electrically conductive channel of radius R and uniform temperature T. An energy-balance equation gives T if R and E are known. In order to complete the analysis Steenbeck[3] postulated that the arc always operates so that, for the given conditions, E is a minimum. This minimum principle is, however, not an essential for the determination of arc data, for we have already shown that the gaseous conduction equations of Section 3 are sufficient to determine completely the arc characteristics and properties. The minimum principle is nevertheless a sound physical principle, for Peters[40] has been able to show recently that the condition of minimum arc voltage or field strength is a special case of the thermodynamic principle of minimum entropy production. The channel model in conjunction with the minimum principle is therefore a reasonable positive-column model and gives[41] calculated characteristics in good agreement with the experimental data of Foitzik.[42]

(4.6) Quasi-Neutrality

So far, we have assumed that the arc positive column is a true plasma, i.e. no net space-charge exists. In practice, the plasma condition is often obtained, because large electrostatic restoring forces are produced when space charges are formed. However, owing to non-uniformities in the arc column, small net space-charges must be produced. Consider the current-continuity equation as given by eqn. (32): then, in general,

$$\rho_e = -\epsilon \frac{\boldsymbol{E} \cdot \nabla\sigma}{\sigma} \quad . \quad . \quad . \quad . \quad . \quad (37)$$

Thus, whenever a field component exists in the direction of the electrical conductivity gradient a space charge must be set up. Consider the cylindrically symmetric arc; normally, σ has a radial gradient only, and E is axial, and it would therefore appear that ρ_e will be zero. This is not the case, however: owing to the different rates of diffusion of electrons and ions and the necessity to maintain $J_- = J_+$ in a radial direction, eqns. (18) and (19) show that a radial field must be produced which is just sufficient to accelerate the ions and decelerate the electrons to make $J_- = J_+$. This necessary radial field, E_r, is produced by the formation of a space charge such that $\nabla \cdot \boldsymbol{E}_r = \rho_e/\epsilon$, and from eqns. (18) and (19)

$$\boldsymbol{E}_r = \frac{kT}{e} \nabla \log_e n \quad . \quad . \quad . \quad . \quad . \quad (38)$$

In a thermal plasma n and σ are functions of temperature, and calculations show that, for typical temperature gradients, $\rho_e/n \ll 1$. The arc can thus be termed quasi-neutral. It is possible, however, to obtain high temperature gradients near, for example, the electrodes. In these cases the space charges set up must be considered carefully.

(5) THE CATHODE REGION

(5.1) Current Continuity

Section 2 showed that the current transit from gas to metal at refractory cathodes can be explained adequately in terms of thermionic emission. The mechanism operates by virtue of a high field close to the cathode produced by the presence of a positive space-charge. The emitted electrons are accelerated in this field, and produce electron multiplication by collision with other particles. The positive ions thus produced are accelerated to the cathode and, by virtue of their kinetic energy, maintain the cathode at a temperature sufficient for the required emission. For cold cathodes, however, the problem is more complex, and this Section is devoted to a consideration of this problem.

Experimental investigations have shown that the arc cathode-fall voltage is small (about 10 volts), that for the cold-cathode arc the current density can be very high (about 10^6 amp/cm^2) and that the arc terminates at the cathode in a bright and highly mobile spot. It has also been shown that spot formation is favoured by the presence of impurities, oxygen or oxides, surface scratches and insulating oxide layers with bound surface charges,[4,43] that typically refractory cathodes can behave as cold cathodes,[44] and that multiple cathode spots can exist. Weizel and Thouret found that a concentrated spot arc can change discontinuously into an arc without a spot. These examples are merely a selection from a vast fund of experimental knowledge, but the data selected emphasize the important aspects of the cathode emission problem.

To explain the emission mechanism many varied hypotheses have been proposed. As early as 1904 Stark suggested that local hot spots existed at temperatures high enough to give thermionic emission. In the intervening years this proposal has received some support from workers who consider that repressed evaporation may exist, and point out the dangers of considering the problem in terms of known macroscopic physical properties. While this may well be true, no verifiable thermionic theory has yet been put forward. In 1926 Slepian[45] suggested that all the necessary cathode current could be obtained as a positive-ion current produced thermally in the gas close to the cathode.

Langmuir,[46] in 1923, first suggested that a cathode-region space-charge might produce a field sufficient to extract directly the required electrons from the cathode, and in modified form this is the mechanism most usually accepted. Mackeown[47] developed Langmuir's suggestion and showed that a satisfactory theory could be developed for the cathode region on the basis of field emission with suitable values of J_+/J_- at the cathode and current densities of about 400 amp/cm^2. In recent years, however, new current density measurements by Cobine and Gallagher[48] and Froome[49] for mercury arcs gave values of the order of 10^6 amp/cm^2. Both Cobine and Gallagher and Wasserab[50] have shown that Mackeown's theory, in conjunction with the Fowler–Nordheim equations, requires a field of about 10^7 volts/cm for densities of 10^6 amp/cm^2, and that consistency is achieved only with work functions as low as 0·5 volt. Such low work functions are improbable even in the presence of contaminants and surface irregularities. Modified field theories have therefore been proposed to overcome this difficulty. Recourse has been had to an early suggestion of Druyvesteyn,[51] namely that emission is enhanced by the presence of a thin electrically charged insulating layer on the cathode surface. Experiments by Haworth[52] and Llewellyn Jones[53] support this view. Lewis[54] has suggested that surface patch fields have a significant influence on the emission. The effect of simultaneous thermionic and field emission has been investigated by Ecker[55] and Bauer,[56] from which it has been shown that such emission is satisfactory for current densities as low as 10^5 amp/cm^2 when $J_+/J_- = 0{\cdot}1$, temperature = 3000°K, work function = 3·5 volts and a field enhancement of 5 occurs. The simultaneous occurrence of such favourable conditions is not always likely. Ecker and Muller[57] have suggested that account must be taken

of the individual field components rather than the average, and their calculations show that this concept produces an improved agreement between theory and experiment. Recently, Cassie[58] has suggested that the cathode work-function may be lowered sufficiently to give adequate field emission by the presence of a negative space-charge in the metal lattice at the cathode spot. It therefore appears that some form of modified field emission can be evoked to describe the mechanism of particular types of cold-cathode arc, although the precise mechanism will be ill-defined, since the surface conditions cannot be described adequately.

Other possible means of obtaining emission include the effects of photon, ion and excited-particle collision with the cathode. Recently, von Engel and Robson[59] have made a detailed study of emission caused by transfer of atom excitation energy to the cathode. They show that this hypothesis is in agreement with experimental data if a high local saturation vapour pressure (about 10 atm) exists within the arc-cathode contact area, and excitation occurs by radiation. The presence of high vapour pressures, vapour bursts and jets has been the basis of mechanisms suggested by many workers in the past.

(5.1.1) The Contraction Theory.

The problem of cathode-current continuity should not, of course, be considered separately from the problems of voltage requirement of the cathode region, the energy balance and the general appearance and properties of the region. In recent years an approach to this general problem has been made by Ecker. In particular, attention has been focused on a more complete cathode region, including not only the space-charge zone immediately in front of the cathode, but also the transition region in which the conducting column contracts from the positive-column area to that of the cathode-spot area.

The investigation of the contraction zone was initiated by Weizel, Rompe and Schon,[60] who took up again Slepian's concept of ions produced thermally in the gas in sufficient quantity for current continuity. The experiments of Thouret, Weizel and Gunther[61] on the arc without cathode spots showed, however, that further, more general, theoretical development was required, to account not only for the spotless phenomena but also for the discontinuous transitions which can occur between the spot and spotless arc types. Weizel and Thouret[62] showed that in the spotless arc the cathode current is carried almost exclusively by electrons.

Ecker[63] first investigated the problem of thermal ion production, assuming separate contraction and space-charge zones with quasi-thermal equilibrium and quasi-neutrality. He notes three arc types, i.e. (*a*) no contraction, spotless; (*b*) medium contraction, e.g. thermionic arc; and (*c*) extreme contraction, e.g. field arc. The calculations show the important result that with increasing contraction the temperature, T_s, at the boundary between the contraction and space-charge zones increases and can be considerably higher than the positive-column temperature. In particular, for a 35 atm mercury arc the increased temperature is high enough to provide a positive-ion saturation current of the order of the total current required for continuity. It is this increased temperature also which produces the high luminosity of the cathode spot.

In the further development of the problem Ecker[64] considered also the cathode electron emission and showed[65] that a stability diagram can be set up which explains many of the arc-cathode contraction phenomena. Fig. 12 shows a stability diagram giving a plot of the positive-ion saturation current (full-line curves) and ion-defect current (broken curves) against contraction ratio (positive-column-radius/cathode-spot-radius). An arc can exist only where the curves intersect. Generally four stable operating

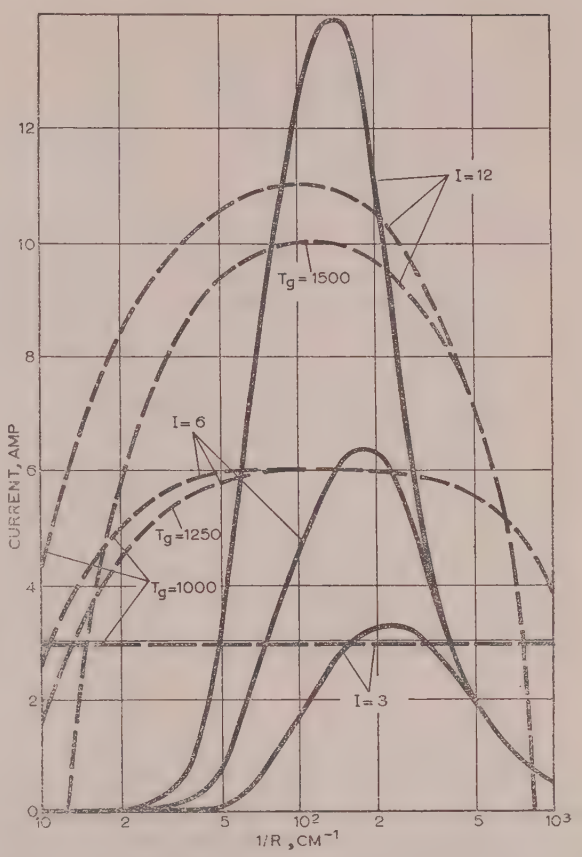


Fig. 12.—Stability diagram for electrode-region conduction (after Ecker).

———— Positive-ion saturation current.
— — — — Total current minus the electron emission current.
I = Total current.
T_g = Gas temperature in cathode region.

points are available, the arc selecting the point giving minimum voltage. This can thus be an explanation for the many diverse arc-spot formations which have been observed. The theory shows that the existence of critical pressures and currents for transition from spotless to spot arcs can be explained in terms of the stability diagram. It must be noted, however, that the theory does not remove the necessity of explaining the actual electron-emission mechanism involved in each condition of stability, so that the question of the precise nature of the emission under extreme contraction remains.

(5.2) The Cathode-Region Voltage

The voltage distribution across the cathode region may be represented diagrammatically by Fig. 13, giving a finer structure then Fig. 2 since we now include the contraction zone. The space-charge zone contributes V_s, the greater part of the voltage drop. The contraction zone contributes V_{cr}. It is seen that this voltage is greater than that of an equivalent length of positive column, the difference increasing with increased contraction. Theoretical investigations of the voltage drops have been mainly concerned with the space-charge zone, and it has been usually assumed that the electrons and ions move through this zone without collision. Thus the zone acts as an accelerating field for the electrons, which produce ions by collision near the

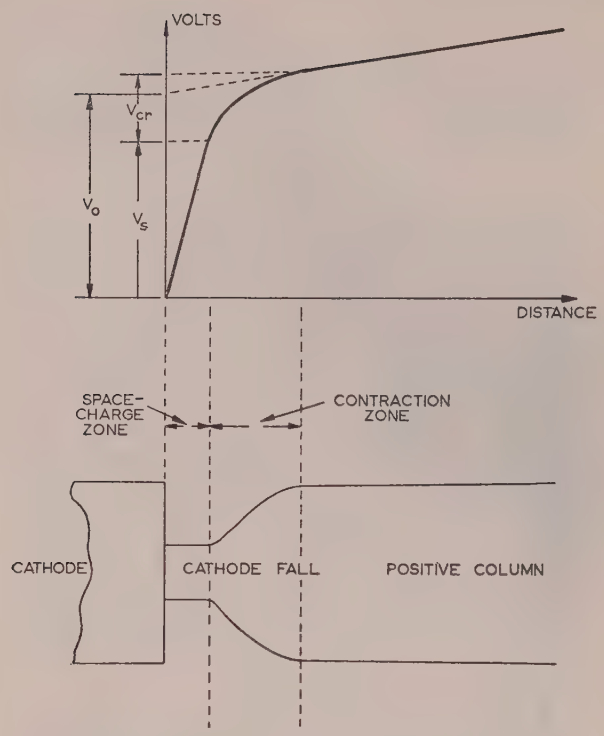


Fig. 13.—Cathode-region potential distribution.

positive-column boundary of the zone. These ions are then accelerated through the zone towards the cathode, and either by bombardment or by virtue of the field itself produce the conditions for current maintenance. Many authors have used this approach with some success. Difficulties arise, however, in the specification of the extension, d_s, of the space-charge zone. Normally d_s is taken as the mean free path, but in these circumstances V_s is sensitively dependent upon d_s. Ecker[66] believes that by accounting for the counter-field diffusion of the electrons from the high-temperature contraction zone, V_s becomes insensitive to d_s and calculation is more accurate. The contraction voltage V_{cr} is also calculable, and for a high-pressure arc $V_s \simeq 6$ volts and $V_{cr} = 4 - 5$ volts.

(5.3) Vapour Jets

Loss of material from the electrodes was one of the first arc phenomenon to be observed. Many investigations have been made on the phenomenon, and electrode vapour jets have been observed and measured[67–75] on arcs with copper, mercury, carbon and tungsten electrodes. Jets have also been observed in the vacuum arc, and in this case they are a particularly important phenomenon. The reaction force on the cathode due to the jets has been discussed and measured by many of the workers noted above. The velocities measured are about $10^5 - 10^4$ cm/sec and the force is about 10^{-5} newton/amp. It has often been noted that the jet is usually preferentially directed.

Many proposals have been made to explain the production and significance of the jets. In particular, it has been suggested that the jets are an indispensable condition for arc maintenance. While this may be true for the vacuum arc, it is unlikely for other arc forms. A thermal region at the cathode for the production of the required vapour is the obvious and most often suggested mechanism. It still remains, however, to explain the measured jet velocities and reaction force, and this is not easy, since, for example, the thermally directed energy of the cathode vapour is too small. Finkelnburg[74] has suggested that in the high-current carbon arc the vapour is heated, expanded and directed preferentially in the contraction zone. Other explanations for the high velocities not calling for thermal-vapour production have been proposed: Risch and Ludi[76] suggest that multiply ionized atoms can be neutralized and reflected from the cathode with high kinetic energy; Haynes[73] also considers the reflection of neutralized atoms and the production of negative ions at the cathode of importance; Holm,[77] on the other hand, suggests the release (sputtering) of high-energy neutral atoms from the cathode by ion bombardment.

Recently, Maecker[78] has shown that plasma jets may be produced artificially by constricting the diameter of a small section of the arc column. He explains these jets in terms of the variation in pinch force along the arc axis. From eqn. (26) it is seen that in the steady state the pressure gradient due to the pinch of the self-magnetic field increases with the current density. Consider the gradients produced at two sections of the column where the current density is different. At each section a radial pressure gradient will exist just sufficient to balance the magnetic pinch forces. Thus in the axial direction a dependent pressure gradient will be produced with effectively no balancing force. This gradient will accelerate the gas along the axis according to eqn. (11) and thus produce a plasma jet. At the cathode the contraction zone provides the variation of current density required by the theory, and it is reasonable to assume that many jets are produced in this manner. However, until further data are available on the coefficient associated with sputtering, neutralization, etc., the possibility of the importance of such processes in particular discharges cannot be ignored.

(5.4) Retrograde Motion: the Arc in a Transverse Magnetic Field

As early as 1903 Stark,[79] and in 1904, Weintraub[80] observed that, when a transverse magnetic field is applied to a vacuum mercury arc, the arc column moves in the direction expected from the field and current directions, but the cathode spot tends to move in the opposite direction. This retrograde motion may so dominate the arc that it moves in the reverse or retrograde direction. The phenomenon has since been observed for widely diverse combinations of electrode materials and gases.[81–87]

As with other arc phenomena, many suggestions have been made to explain the phenomenon,[88–91] but many of these proposals are not in agreement with the experimental data obtained by St. John and Winans.[85] Recently, Ecker and Muller[92] have suggested that only the extreme contracted cathode spot will give retrograde motion. In this case they suggest that, owing to the extreme contraction, diffusion electrons cannot compensate the positive space-charge and a potential tube is formed. The cathode-emitted electrons follow this tube until their energy is sufficient to overcome the radial potential wall. The ion path, and with it the tube axis, is deflected by a magnetic field in the normal direction. The electrons from the cathode therefore develop effectively a retrograde velocity and break through the tube on the retrograde side. By fitting at one point the theory appears to give good agreement with experiment.

(5.5) The Energy Balance

For many considerations of cathode phenomena, the energy balance is of importance.[93–95] A complete calculation of the balance is hardly possible, since many of the coefficients required are not known. We only indicate here some of the forms of energy which must be considered. The energies supplied to the cathode are by bombarding positive ions,

neutralization energy transfer, condensation energy of the ions, heat conduction from the gas, radiation and possible chemical reaction. The energy losses from the electrode are due to electron emission, vaporization, loss of metal globules, radiation and heat conduction through both solid and surrounding gas.

(6) THE ANODE REGION

In many ways the anode region is similar to the cathode region. Thus a contraction region is observed, although less sharp than at the cathode, and a space-charge zone exists for the production of the positive ions required by the positive column. Except for the Beck arc, the anode does not emit positive ions, so that the full quantity required for the column ion conduction must be supplied by the anode region. However, since $J_+ \ll J_-$, the anode-region conditions are not so extreme as the cathode conditions. Ecker has shown that the cathode contraction theory can be applied to the anode by use of a transformation factor.

In a series of investigations, Busz-Peuckert and Finkelnburg[96] have measured the anode properties of the argon and nitrogen arcs. Using probe techniques they show, for example, that the anode voltage depends upon both current and gap length, having values between 5 and 10 volts. The potential distribution in the anode space-charge zone has been intensively studied by Bez and Hocker,[97] who ignore the contraction zone but divide the space-charge zone into an accelerating zone commencing at the positive-column end of the region and in which the electrons entering from the positive column are accelerated without collision, and a succeeding ionization zone immediately in front of the anode in which the necessary ions are produced. Their calculations of potential show that this form of field ionization gives good agreement with known data if the positive-column/anode-region boundary temperature is between 6000 and 8500°K. At higher temperatures they suggest that thermal ionization in the anode region tends to become important, and that, in association with this, the anode region contracts radially. In this manner they explain the transition from the low-current carbon arc to the high-current carbon arc which has a greater anode contraction and current density.

The calculation of the energy balance at the anode is simpler than that at the cathode, since a number of the coefficients involved are more definite. Finkelnburg[74] has investigated the balance for the high-current arc anode in great detail. In his work he also assumed thermal ionization in the region of the anode fall. Cobine and Burger[94] have also calculated the anode energy balance of short-duration high-current carbon arcs. They conclude that the anode is supplied with 0·05–1·0 MW/cm^2 and that most of this power is consumed in metal vaporization, so that a high anode vapour pressure exists. This is then the source of vapour for the anode vapour jets which are readily observed and which have been often reported (see references in Section 5.3). In general, the jet theory at the anode is simpler than at the cathode, since many of the cathode processes are not repeated at the anode.

(7) SPECIAL ARC TYPES

It is worth while to give a separate brief description of some arc types which are of special interest.

(7.1) The Carbon Arc in Air

The carbon arc deserves special mention if only because of the numerous investigations made upon it and because so many important phenomena have been observed in it. Certain rather arbitrary sub-classifications may be used.

The Low-Current Arc.—This term is usually applied to the arc carrying from a few amperes to, say, 50–75 amp. The properties of high electrode luminosity are well known, and on pure carbon the cathode- and anode-spot temperatures are about 3000 and 4000°K respectively, the current densities at the cathode and anode being about 500 and 40 amp/cm^2. The arc is characterized by a bluish central core having a temperature of about 6000°K and a surrounding flame. A total voltage of about 50 volts at 10 amp is typical.

The High-Current Arc.—At about 50 amp a brighter central core begins to develop in the positive column, owing to the decrease in thermal conductivity with completion of dissociation of nitrogen.[15] With further current increase the cathode spot contracts and pinch forces produce axial gas streaming.[78] This accentuates the core contraction, resulting finally in a tenfold increase in current density at about 130 amp. Simultaneously with the column and cathode changes, marked and even more important changes occur at the anode. In the low-current arc the anode current density is about 40 amp/cm^2 and vaporization is only slight. This density does not change until the total anode front surface is covered by the arc spot. When this condition is reached the current density increases, causing intense vaporization and the production of a large anode flame. Within this flame the temperature is about 8000°K. A consequence of this anode condition is an increasing anode-fall voltage with increase in current, which thus produces a rising or positive voltage/current characteristic. With the onset of the anode flame and positive characteristic and the development of the contracted column the arc is in its fully developed high-current form. Reference should be made to the treatise by Finkelnburg[74] on this discharge.

The Beck Arc.—The anode flame of the high-current pure-carbon arc is of relatively small visible brilliance. However, if the anode is cored with cerium and other rare-earth compounds, the anode-flame vapour emits radiation fairly uniformly over the visible range with resultant great brilliance. This type of arc, known as the Beck arc after its discoverer, is greatly used for illumination purposes. In this arc, also, positive ion emission from the anode becomes important.

The D.C.X. Arc.—Recently, use has been made of the vacuum carbon arc in thermonuclear fusion experiments. It has been found that this arc has a high efficiency for dissociating a beam of molecular ions which may then be trapped if the arc is run, for example, in a magnetic-mirror configuration.[98]

(7.2) The Mercury-Vapour Arc

The arc in mercury vapour can be operated between any electrode materials, but when using a mercury-pool cathode it is particularly interesting for it shows the high cathode-spot mobility and other typical characteristics of a cold-cathode arc. The arc is used mainly for illumination and rectification purposes. The nature of the discharge is sensitively dependent upon the vapour pressure, which is determined by the power input and arc enclosure. Used as a light source with low vapour pressure, we have the normal fluorescent lamp. As the vapour pressure is increased the luminous efficiency reaches a maximum and then decreases. Further pressure increase causes a contraction of the discharge with a rise in both the gas temperature and luminosity, the contracted discharge being defined as a high-pressure arc. As the pressure of this arc form is increased further, predominantly thermal radiation is produced. The mechanism of the high-pressure discharge has been extensively studied and described by Elenbaas,[35] who used a discharge 50 cm long at a pressure of 0·88 atm, with an input power of 35 watts/cm. In this condition the gradient was 5·8 volts/cm and the effective temperature 5550°K. An attempt has been made by Hoyaux[99] to apply the fundamental principles of arc theory to the design of rectifiers, apparently with some success.

It is clear that further developments along these lines will prove beneficial.

(7.3) The Welding Arc

The heat generated in all the main arc regions is used either directly or indirectly to melt metals and consequently produce welding. Normally, the workpiece is made the anode in order to utilize the higher electrode temperature, although even with this condition there may well be a heat contribution from the positive column and a net radiation gain from the cathode. With the welding arc, normal arc theory is further complicated by the essential processes of metal transfer from the weld rod to the workpiece and also normally by the presence of complex electrode coatings which affect the arc composition. The metal transferred by normal electrode jets is not sufficient for welding purposes so that rod electrodes are used which, with currents of 50–300amp, melt by a combination of resistance and arc heating, and the molten metal is ejected from the electrodes in the form of globules or fine spray. The forces moving the metal across the gap to the workpiece may be a combination of surface tension, gravity, electromagnetic pinching at the neck of a globule and the axial pressure gradients causing the electrode jets. This latter phenomenon is the case of arc stiffness, which is so useful, for example, for overhead welding. In practice, the conditions of electrode mass, composition and coating, gas, arc length and current must be determined for each particular type of weld.

In recent years a major advance has been made in welding by the use of controlled gas shielding of the arc.[100–102] The gas is fed at about 5–10ft/sec from a nozzle around the electrode, so that the arc operates effectively in the gas supplied. The use of gas-shielded arcs permits the welding of aluminium, titanium super alloys and certain grades of stainless steel. Argon and inert gases have been mainly used, although carbon dioxide and other gases are being tried. The success of gas-shielded welding appears to be due to the unique axial spray transfer which occurs under proper conditions. Furthermore, with inert gases the workpiece is shielded from oxygen, so that, with aluminium, for example, it is not possible for the tenacious oxide to form. With bare electrodes it is found that the electrode must be made positive for the spray to be produced. Lesnewich[101] shows that at low currents metal transfer takes place in the globular form, of a size frequently larger than the electrode diameter, e.g. drops of $\frac{1}{8}$in diameter at a rate of five a second. With increase in current the drop size diminishes and the rate increases, although a critical current is reached when discontinuities occur in these quantities. Thus, with $\frac{1}{16}$in-diameter mild-steel electrode at 250amp the rate increases from 15 to 240 drops/sec and the drop diameter changes from 0·16 to 0·04in, the transfer then being in the form of a directed spray. Gas-shielded arcs can now be used with both polarities and on alternating current if activated electrodes are used. Thus, by coating the electrodes with an extremely dilute solution of rare earths, an atomic film is formed during arc operation which reduces the work function and allows stable cathode operation at the welding electrode.[103, 104]

The development of inert-gas welding has stimulated careful investigations into the characteristics of these arcs. The early work of Doan and Myer[105] showed the stabilizing influence produced on low-current argon arcs by small quantities of oxygen. Skolnik and Jones[106] have given voltage/current/length characteristics of argon-helium d.c. arcs from 20 to 100amp. Further work is reported in the symposium on inert gas arcs of 1956.[107] A recent development for metal cutting and possible welding is the use of a plasma jet;[108] in this form of apparatus an arc discharge is blown on axially by a high-velocity gas, so that the plasma is forced through an orifice in one of the electrodes. The plasma emerging from the orifice may have temperatures up to 50000°K.

(7.4) The Circuit-Breaker Arc

The arc produced by switch operation causes intense vaporization of any liquid medium and of the solid electrodes, so that the arc operates in a complex gas mixture which may have appreciable mass velocities. The essential interruption problem is to understand the dynamic behaviour of the arc as the current is reduced, either artificially or by use of an alternating current, and to determine the arc and gas-conduction properties in the short period of time about current zero. Slepian's[109] early work on the analysis of recovering gaps is noteworthy. Dynamic energy-balance equations based on thermal losses have been set up by Cassie[110] and Mayr,[111] and Browne[112] has analysed the two approaches.

Despite the tendency for empirical development, there exists a history of controlled experiment on the recovery of the arc-gap subsequent to current zero. Thus Slepian measured the recovery of the gap by varying the rate of rise of restriking voltage and determining the breakdown value at different times after current zero. Work by Todd and Browne[113] and Cobine[114] and his associates are noteworthy developments of Slepian's method. In all this work the recovery of the gap is measured with the presence of energy input from the restriking voltage. Recently the author[115–117] and his colleagues have studied the 'free' recovery, i.e. recovery in the absence of restriking voltage. The work of many investigators shows that cold-cathode arcs after interruption recover almost immediately to the glow cathode-fall voltage. Refractory arcs due to the maintenance of thermionic emission recover relatively slowly to this condition. Subsequent recovery is due mainly to the gradual temperature fall of the arc column and the consequent reduction in thermal ionization. When the gap ionization is negligible the gas density is still lower than normal and restrikes via spark breakdown can occur at voltages lower than the normal breakdown value. For an artificially interrupted d.c. carbon arc of 20amp we have measured the free recovery of gas temperature, gap resistance, instantaneous power loss and breakdown voltage. Typical curves are given in Figs. 14 and 15. Calculations by Whittaker[118] show that these properties can be explained in the main by an analysis based upon energy loss by thermal conduction, and calculated temperature decay distributions are given in Fig. 16.

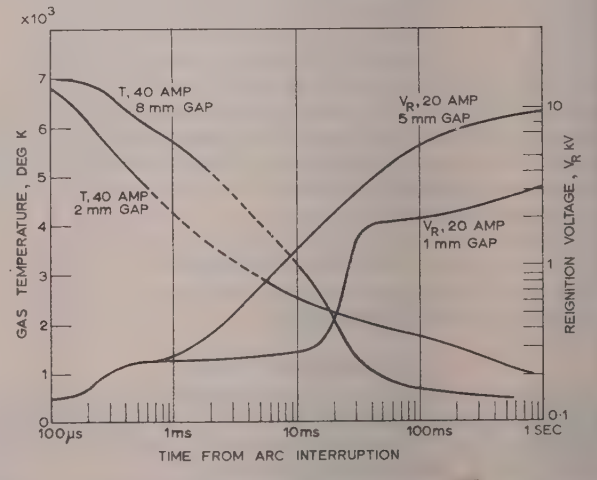


Fig. 14.—Free recovery of gas temperature, T, and reignition voltage, V_R, of carbon arc in air.

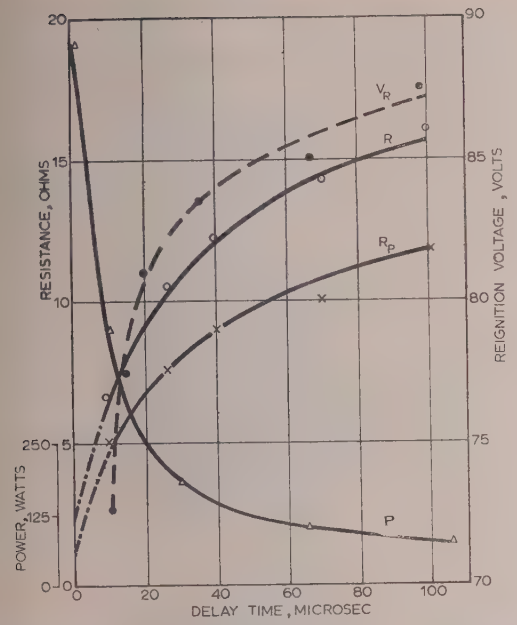


Fig. 15.—Free recovery of reignition voltage, V_R, total arc resistance, R, positive-column resistance per centimetre, R_p, and total power dissipation, P, of 20 amp 5 mm carbon arc in air.

Measured by S. Y. Ettinger in this Department.

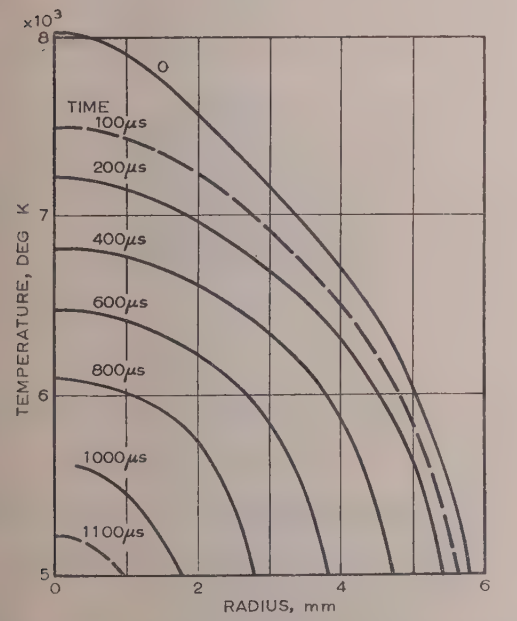


Fig. 16.—Theoretical curves of free radial temperature decay of nitrogen positive column, wall stabilized, and losses by thermal conduction only.

Initial conditions.—58 amp, 1·3 volts/mm, atmospheric pressure.

Wienecke's[119] and Frind's[120] investigations of arc decay should also be noted.

Recently the use of vacuum arcs and arcs in electronegative gases has been investigated for interruption purposes. The vacuum arc operates in the electrode vapour produced by contact separation, and experiment[121] shows the existence of rapid diffusion of the charged particles with many short-period restrikes as the electrodes separate. The switch finally recovers when gap separation is sufficient to withstand restriking due to the presence of metal vapour or field emission. The particularly useful property of the vacuum interrupter is the high breakdown strength of the very-low-pressure gas. Owing to gas clean-up the vacuum pressure does not increase, despite the evolution of electrode gas and vapour, so that the high breakdown strength is maintained. The use of electronegative gases, e.g. sulphur hexafluoride, is proving advantageous in switchgear, owing to the reduction of the remnant electrical conductivity by electron attachment and to the high electric strength of the gas. Examples of this form of arc interruption are described by Lingal, Strom and Browne[122] and Browne and Leeds.[123]

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EROSION OF CONTACTS BY ARCING

The Effect of Current Waveshape and Other Factors

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SUMMARY

The effect of the current waveshape on the rate of arc erosion is studied for currents of 180–1 090 amp, with contacts of molybdenum, steel and a sintered mixture of tungsten and copper. The amount of arc erosion is found to increase with the current amplitude for a constant arc charge. It is not linearly proportional to either the arc charge or its current amplitude. It increases with the current amplitude at an increasing rate over the range of tests. It is found to be sensitively affected by the contact separation in the millimetre range.

LIST OF PRINCIPAL SYMBOLS

W_a, W_c = Energy input to the anode or cathode mark.
I = Arc current.
V_a, V_c = Anode and cathode voltage drops.
V_T = Voltage representing the thermal energy of the electrons at the anode.
V_i = Ionization voltage of the gas medium of the arc.
ϕ = Work function of contact surface.
W_{ra}, W_{rc} = Heat received by the anode or cathode mark in the form of radiation from the arc column.
W_n = Energy delivered to the anode mark by the impinging neutral atoms.
γ = Fraction of the current carried by positive ions at the cathode spot.
ν = Fraction of the energy of positive ions delivered to the cathode.
W_{ca}, W_{cc} = Heat conducted into the contact material at the anode or cathode mark.
W_{eva}, W_{evc} = Heat consumed in evaporating metal from the anode or cathode mark.
m = Weight of metal evaporated from the anode or cathode mark.

(1) INTRODUCTION

The phenomenon of contact wear due to arcing has received considerable attention over the years. It is, however, far from being completely resolved. Although it is known that the rate of arc erosion depends upon many factors such as the arc current, the arc-current waveshape has not so far been expressed as an explicit variable affecting the rate of arc erosion. The amount of contact has usually been expressed as a function of either the circuit-elements,[1] the arc charge,[2, 3] or the arc energy,[4] the effect of the arc-current waveshape not being clearly stated.

On the other hand, Baxter[5] found that the rate of contact wear of contactors in a.c. circuits increases with the current, but, in his work, he used alternating currents without controlling the arc duration. Therefore, his conclusion needed further clarification and study. Wilson[6] varied the arc charge simultaneously with the amplitude of the current wave, and thus the effect of each variable on the rate of contact erosion could not be obtained separately. In the investigation of Cooper and Riddlestone[7] the rate of erosion was found to depend upon the circuit current, but the effects of arc charge and contact separation were not isolated.

The purpose of the present paper is to show that, even for the same arc charge and all external conditions, the rate of arc erosion varies with the amplitude of the arc-current wave. The mode of this variation is studied, and an attempt is made to explain it.

(2) EXPERIMENTAL INVESTIGATION

A current-surge generator (Fig. 1) was used for generating current waves of the shape displayed in Fig. 2. The resistance

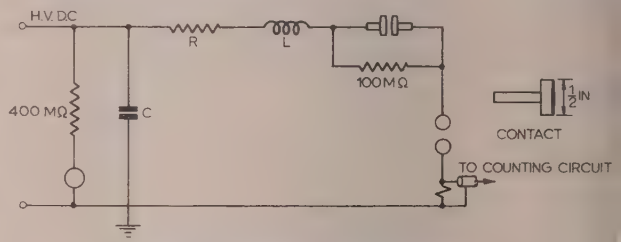


Fig. 1.—Connection of the test circuit.

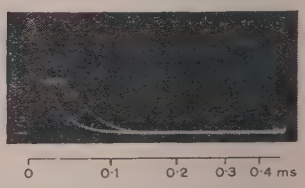


Fig. 2.—Two current waves of amplitudes 550 and 1 090 amp, with the same charge of 38 mC.

across the pair of contacts under test (Fig. 1) allows the full voltage of the capacitor C to be applied across the sphere-gap at each discharge, thus ensuring consistency of its breakdown and of the current waveshape for each circuit arrangement. The resistance has a large value of 100 megohms, and thus it would draw a current of about 0·1 mA, which is a negligible fraction of the total circuit current which would be assumed to flow in the arc between the contacts under test. With the charge which flows through the arc maintained constant at either 38 or 73 mC, the current amplitude was varied between 180 and 1 090 amp, by suitably adjusting the circuit-elements R and L, as indicated by the following expression:

$$I_p = V\left(\frac{\alpha-\beta}{\alpha+\beta}\right)^{\alpha/2\beta} \Big/ L(\alpha^2-\beta^2)^{1/2} \quad . \quad . \quad . \quad (1$$

where $\alpha = R/2L$ and $\beta = (R^2/4L^2 - 1/LC)^{1/2}$.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

Prof. El-Koshairy was formerly Head of the Department of Electrical Engineering University of Cairo, and is now Secretary General of the Electricity Commission of the United Arab Republic.
Dr. Khalifa is in the Department of Electrical Engineering, University of Cairo.
Mr. Aboul-Makarem was formerly at the Royal Institute of Technology, Sweden, and is now in the High Power Laboratory, A.S.E.A., Sweden.

The charge which flows through the arc was made constant by fixing the capacitance C at 3·5 and 6·67 μF for the respective charges of 38 and 73 mC; the charging voltage being fixed at 12 kV. The residual voltage of the capacitor C after the discharges was measured and found to be practically constant at 1·1 kV with a scatter of $\pm$100 volts. The charge which flows through the arc is taken as the difference between the original and residual charges in the capacitor C. The error in these values of charge would be within $\pm$1%. This charge which flows through the arc will be referred to in the following parts of the paper as the arc charge.

It is known that the rate of arc erosion depends upon the contact shapes and separation, as well as the rate of arcing.[5] Therefore, in order to obtain reliable results, all these variables were made constant, while either the arc-current amplitude or charge was varied. The contacts were arranged in a horizontal disposition and had the shape indicated in the insert of Fig. 1. Their separation was set at values between 0·5 and 1·5 mm. The charging voltage of C was fixed so as to eliminate the effect of variation of the charge on the capacitance between the contacts. The charging voltage was sufficient to break down the sphere-gap and the gap between the contacts, and to initiate the arc, thus obviating the necessity of causing the contacts to touch and eliminating the bridge metal-transfer. In all the experiments the ambient medium was atmospheric air. The rate of arcing was essentially constant at 1 discharge/min, and counting of the discharges was carried out by an electric circuit. For plotting each point on the given curves, a series of discharges was run between a new pair of contacts just after being thoroughly polished, washed, dried in a desiccator and weighed by a microbalance. As the microbalance had an accuracy of $\pm$2 μg, the number of discharges per series was such that the loss or gain per contact would be about 100 μg to have an error in weight of only $\pm$2%. The number of discharges per series was usually greater than 300, which is believed to account fairly well for the statistical variation in the erosion per discharge. Thus the repeatability of the measured weight per series was not checked because it was time-consuming—more than five hours of experimental work being needed for each point on the curves. The investigated contact materials were molybdenum, steel and a sintered mixture of tungsten and copper in the ratio 7 : 3. The arc-current wave parameters were measured by oscillograph records.

(3) DISCUSSION OF RESULTS

The experimental results are plotted in Figs. 3, 4 and 5. It is preferred to handle the discussion of these results from two angles; namely the variation of current amplitude with a constant charge, and the variation of the arc charge for a constant current amplitude.

(3.1) Effect of Variation of Current Amplitude with Constant Arc Charge

With the arc charge maintained constant at 73 mC, the current amplitude was varied between 180 and 1090 amp. The rates of arc erosion were measured at a contact separation of 1 mm and for various current amplitudes. The results are plotted in Fig. 3 for the above-mentioned materials. It is noted that the metal losses from both the cathode and anode are not constant for a given arc charge; they increase and become more sensitive to current changes at the higher current amplitudes. For example, for molybdenum contacts at 1 mm separation, the rate of contact erosion is roughly proportional to the fourth root of the current amplitude at 200 amp, and is almost linearly proportional to the amplitude at 1 kA. These ranges were found to depend upon the contact material, and may also depend upon the contact separation and the order of magnitude of the arc charge.

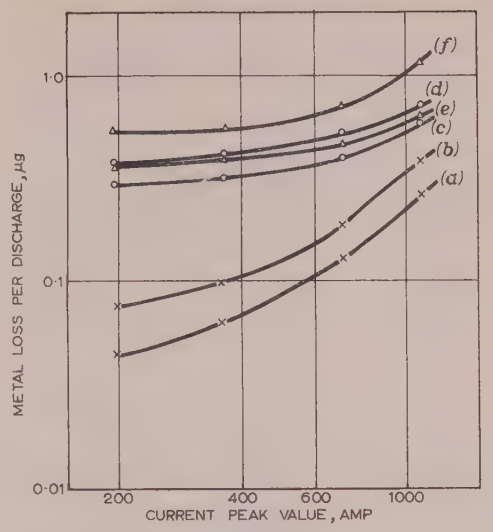


Fig. 3.—Rates of arc erosion for an arc charge of 73 mC with different current amplitudes.

(*a*) Rate of loss from molybdenum anode.
(*b*) Rate of loss from molybdenum cathode.
(*c*) Rate of loss from steel anode.
(*d*) Rate of loss from steel cathode.
(*e*) Rate of loss from tungsten-copper anode.
(*f*) Rate of loss from tungsten-copper cathode.
The contact separation was fixed at 1 mm.

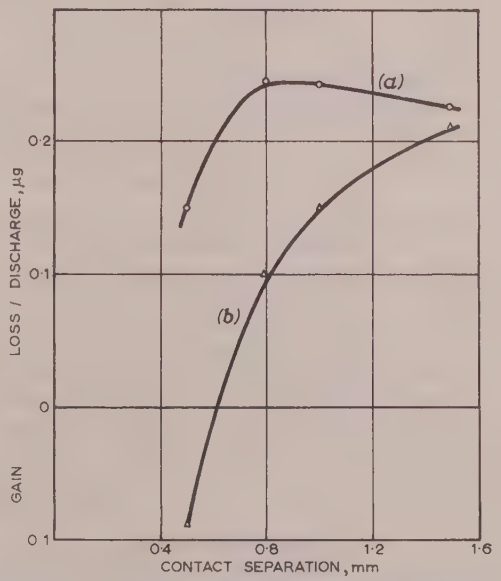


Fig. 4.—Effect of contact separation on the contact erosion at an arc charge of 38 mC and a current amplitude of 550 amp, with steel contacts.

(*a*) Cathode. (*b*) Anode.

It is also noted that the rates of contact erosion for both the cathode and anode are quite sensitive to variation in the contact separation as indicated by Fig. 4, for steel contacts at a constant current amplitude of 550 amp and an arc charge of 38 mC. The hump in the cathode loss curve may be the result of two opposite factors which would come into play with the reduction

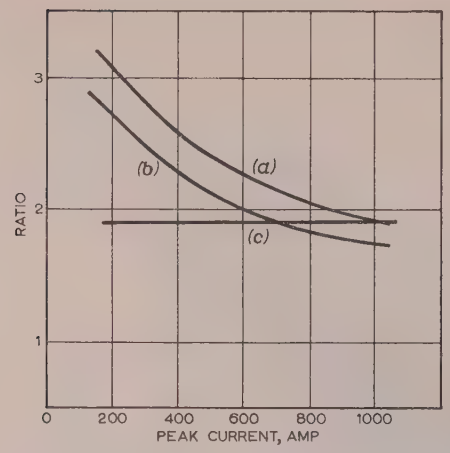


Fig. 5.—Ratios of anode and cathode losses at an arc charge of 73 mC to those at 38 mC for different current amplitudes with steel contacts 1 mm apart.
(*a*) Cathode loss.
(*b*) Anode loss.
(*c*) Ratio of charges.

of contact separation, namely the increased ejection of liquid metal by the violent expanding gas confined in the space between the contacts, and the greater portion of metal vapour condensing on the cool parts of the cathode surface.

With further reduction in contact separation, the cathode loss is considerably reduced, which may be ascribed to increased metal-vapour condensation. The same phenomenon may account for the net gain in the anode at such small separations.

The metal loss from the cathode is greater than that from the anode, probably because of the higher current density[8] and the correspondingly higher input to the cathode. A more rigorous explanation of this point might await measurement of the cathode and anode voltage drops for transient arcs.

(3.2) Effect of Variation of Arc Charge for Constant Current Amplitude

The experiment of Section 3.1 was repeated at two different arc charges of 38 and 73 mC, with steel contacts 1 mm apart. For each current amplitude in the range of 180–1 090 amp, the contact erosions corresponding to the two values of arc charge were compared, and the ratio between them is plotted in Fig. 5. Curve (*a*) indicates the ratio of the cathode loss at 73 mC to that corresponding to 38 mC for the same current amplitudes. The curve also shows the variation of this ratio with the current amplitude. Similarly, curve (*b*) gives the ratio of the anode losses, while curve (*c*) indicates the ratio of the arc charges (73 : 38) for comparison.

From Fig. 5, it is seen that, for the present case of steel contacts 1 mm apart, if the peak current is fixed and the arc charge is increased, the erosion of the cathode and anode would increase more than proportionately. The ratio of the contact losses does not equal that of the arc charges except at the higher current amplitudes and over a limited range, 800–1 000 amp, in the present instance of steel contacts 1 mm apart. This implies that the arc charge may not be a direct variable proportionately affecting the arc erosion. In the following Section an attempt is made to clarify the absence of this direct effect of the arc charge on the rate of contact erosion.

(4) THEORETICAL ANALYSIS

In this analysis, only metal evaporation from the molten areas covering each of the anode and cathode spots will be considered; i.e. metal-vapour condensation on the contacts and the corresponding heat transfer thereto will not be taken into account. It is assumed that the net metal loss is roughly proportional to the amount of metal evaporated, as previously found by Holm.[4] The analysis will take into account the energy balance at each of the anode and cathode marks, which are the molten areas that cover each of the arc terminal spots on the anode and cathode.

Considering the energy balance at the anode mark, the energy input during the arc period t_a is equal to the energy consumed at the anode mark as expressed by the following relation, neglecting heat loss by radiation, which would be about 1% or less:

$$W_a = \int_0^{t_a} I(V_a + V_T + \phi)dt + W_{ra} + W_n \quad . \quad . \quad (2)$$

$$W_a = W_{ca} + {}^{v}W_{eva} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

For the cathode the corresponding relation would be

$$W_c = \int_0^{t_a} I(\gamma\nu V_c + \gamma V_i - \phi)dt + {}^{v}W_{rc} \quad . \quad . \quad . \quad (4)$$

$$W_c = W_{cc} + W_{evc} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The voltages V_T, V_i, the work function ϕ, and the factors γ and ν may be taken as constant, while V_a and V_c are not yet definitely known for transient arcs. In static arcs, the electrode voltage drops were found to decrease for increasing currents[9, 10, 11] according to a drooping characteristic similar in shape to that of the total arc voltage. Under dynamic conditions, however, the cathode voltage drop and the arc column voltage were found to increase with the arc current,[12] for frequencies above 100 c/s, at currents of about 10 amp. In the present discussion of dynamic arcs with durations of about 0·1 millisec, the anode and cathode voltage drops will be conservatively taken as constant. Their increase with current would further augment the argument.

The input by radiation to the anode and cathode marks, W_{ra} and W_{rc}, is about 10% of the input by the electric current.[8] Also, the input to the anode by the impinging neutral atoms, W_n, may be safely neglected.[8]

The heat conducted into the contacts may be assessed by approximating the anode or cathode mark to a hemisphere of molten metal of radius r_m much smaller than the dimension of the contacts. Its surface temperature is assumed to rise from the ambient temperature T_a to the melting temperature T_m of the contact metal, according to a step function. This may be justified, as the heating period of the electrode spots was stated[13, 14] to be about 10^{-2} microsec, compared with present arc durations of about 0·1 millisec. Thus the heat conducted into the anode mark, e.g. over the arc duration t_a, was calculated to be

$$W_{ca} = 2k(T_m - T_a)[2\pi t_a + r_m\sqrt{(t_a\rho c/\pi k)} \quad . \quad . \quad (6$$

where k = Thermal conductivity of the contact material.
ρ = Its density.
c = Its specific heat.
All at the melting temperature.

For an electrode mark of about 0·1 mm in size, and for an arc duration of 0·1 millisec, the conduction loss is estimated at about 30% in case of steel contacts, and about 70% in case of molybdenum contacts, compared with the electrical input given by Cobine *et al.*[8] These ratios seem to be rather high; nevertheless, it is believed that they correctly imply that heat conducted within the contacts under the studied conditions might comprise a significant part of the energy dissipated. It is also

indicated that heat conducted in molybdenum contacts is greater than that in steel contacts.

The anode mark was found to increase roughly proportionally with the arc current,[13] and was also found to increase with the arc duration.[4] Therefore, if the current is inversely proportional to the arc duration as in the present case of constant arc charge, the anode mark may be assumed to have an essentially constant area. The cathode mark is similarly treated. Thus the electrical inputs expressed by the first terms of eqns. (2) and (4) are taken as constant, and the heat input by radiation and loss by conduction are assumed to depend mainly upon the arc duration.

The weights of metal eroded from either the anode or cathode mark would thus be expressed by a relation of the form

$$m = aQ + bt_a - c\sqrt{t_a} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where a, b and c are constants depending upon the contact material and whether the contact is the anode or cathode. They would also depend upon the contact shape and separation.

Eqn. (7) shows that the weight of eroded metal is not linearly proportional to the arc charge Q, owing to the significance of the latter two terms of the relation.

It is noted that, for a fixed arc charge, if the current amplitude increases and the arc duration correspondingly decreases, the value of the last term of eqn. (7) would be less negative, and the amount of metal eroded would increase. Further, the heat conducted in molybdenum contacts would be more significant than in steel contacts as mentioned above. This would account for the rate of contact erosion for molybdenum being of lesser magnitude and of higher sensitivity to variation of the current amplitude than steel, as shown in Fig. 3 and as implied by the greater magnitude of the last term of eqn. (7) for molybdenum than for steel.

If the current amplitude were kept constant and the arc charge were increased by increasing the arc duration, the first term of eqn. (7) would increase almost linearly, while the last term would increase less than linearly. Correspondingly the amount of metal eroded, m, would increase more than linearly with the arc duration and the arc charge. In other words, the ratio of the metal loss at an arc charge of 73 mC to that at 38 mC would be greater than the ratio of the charges, in agreement with the results shown in Fig. 5.

At higher current amplitudes and the correspondingly shorter arc durations, however, the last two terms of eqn. (7) would have a less pronounced effect, and thus the ratio of the contact losses would approach the ratio of the arc charges.

The calculation of the coefficients a, b and c of eqn. (7) to any degree of accuracy, using the theories of contact erosion so far available, would be rather difficult. A better approach might be to evaluate these coefficients from the experimental results plotted in Fig. 3. Therefore, the relation is preferably rewritten in the following form, noting that the current amplitude I is approximately inversely proportional to the arc duration t_a in the present cases of constant arc charges Q:

$$m = aQ + b'Q/I + c'\sqrt{Q}/\sqrt{I} \quad . \quad . \quad . \quad (7')$$

Thus, replotting the curves of Fig. 3 to an abscissa of $1/\sqrt{I}$, as illustrated in Fig. 6, the coefficients a, b' and c' could be obtained to validate eqn. (7') within the range of the experiments in Section 3.1. As an example, the relation would take the following form for the molybdenum cathode at 73 mC, and 1 mm contact separation:

$$m = 0{\cdot}012Q + 2{\cdot}69Q/I - 2{\cdot}95\sqrt{Q}/\sqrt{I} \text{ microgrammes per discharge}$$

The values of m obtained from this equation are indicated by the dotted line in Fig. 6 for comparison with the solid line which indicates the corresponding experimental results. The deviation is within $\pm 10\%$.

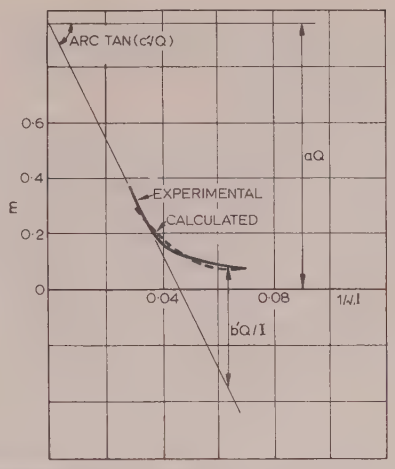


Fig. 6.—Evaluation of the coefficients a, b' and c' for the case of molybdenum cathode of curve (b) of Fig. 3.
m is in microgrammes per discharge.
I is in amperes.
Q is in millicoulombs.

Meanwhile, using the experimental results of Section 3.2, the validity of eqn. (7') was checked for change of arc charge from 73 to 38 mC, and the coefficients a, b' and c' were found to remain essentially constant within about 10%

Before attempting to generalize eqn. (7') for rate of contact erosion due to arcing, the underlying assumptions made at the beginning of this Section should be further checked for other contact materials and over a wider range of arc current, charge and contact arrangements.

(5) CONCLUSIONS

The effects of arc charge and current amplitude on contact erosion were studied for fixed external conditions.

For a certain arc charge, the rate of contact erosion was found to depend upon the waveshape of the arc current, and to increase with the current amplitude, over the range of tests.

The sensitivity of arc erosion to changes in arc current was found to increase at the higher current amplitudes. This sensitivity was found to be more pronounced for molybdenum than for steel in the range of the present tests.

The erosions of both the anode and the cathode were found to be sensitive to changes in the contact separation in the tested millimetre range.

(6) ACKNOWLEDGMENT

The authors wish to express their thanks to Professor Hammam Mahmoud, Head of the Electrical Engineering Department, Faulty of Engineering, University of Cairo, for the use of the facilities of the High Voltage Laboratory, and to Dr. Fouad Taher for his helpful discussions and keen interest in the work.

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DISCUSSION ON 'DEVELOPMENT OF HIGH-VOLTAGE AIR-BREAK CIRCUIT-BREAKERS WITH INSULATED-STEEL-PLATE ARC CHUTES'*

WESTERN CENTRE, AT BRISTOL, 11TH APRIL, 1960

Mr. H. S. Davidson: There has been discussion on the fire risk inherent in oil circuit-breakers. In my view this has been much exaggerated, and under normal circumstances would not be decisive in any choice between air or oil circuit-breakers. It has also been implied that current chopping must be expected with oil circuit-breakers, but I am sure that the authors do not mean this to be accepted without some reservation.

The C.E.G.B. requirements for switchgear of this type are mainly in connection with power-station auxiliaries, and the specification permits the use of air or oil circuit-breakers, despite the fact that some trouble with breakdown of the insulation of high-voltage motors has been experienced.

Would the authors agree that these troubles cannot be attributed to the switchgear, and that either type can be equally satisfactory for this duty?

Messrs. F. S. Fay, J. A. Thomas, D. Legg, and J. S. Morton (*in reply*): In the majority of applications of oil circuit-breakers the fire hazard may be disregarded, but where repeated load operations between maintenance periods occur or a number of consecutive short-circuits are cleared, heavy oil carbonization may depress the insulation security to a level where a bushing flashes over, resulting in an explosion and oil fire. In such circumstances an air-break circuit-breaker offers advantages.

Tests have shown that oil circuit-breakers produce higher over-voltages due to current-chopping than air circuit-breakers, but there is insufficient evidence to show that these over-voltages are by themselves the cause of motor insulation failures.

* FAY, F. S., THOMAS, J. A., LEGG, D., and MORTON, J. S.: Paper No. 2746 S, November, 1958 (see **106** A, p. 381).

DISCUSSION ON
THE APPLICATION OF LOW-PRESSURE RESINS TO SOME HIGH-VOLTAGE SWITCHGEAR DESIGNS'*

NORTH-WESTERN SUPPLY GROUP AT MANCHESTER, 23RD FEBRUARY, 1960

Mr. J. R. Ferguson: I would confirm that, after considerable development work, the best combination of resin and hardener for high-voltage work of this nature appears to be Araldite B with the hardener phthalic anhydride.

I agree that epoxide resins are superior to s.r.b.p., as they are not only isotropic but are non-hygroscopic to a high degree. Furthermore, even with internal discharges they have a very long life. An example of this is where an 11 kV current transformer, having an internal discharge of over 200 pC at 7 kV, has been energized at 20 kV for over 4 000 hours without breakdown.

The suggested level of 200 pC maximum discharge at the working voltage plus 15% is reasonable, although in the majority of cases no discharge at all can be seen on the detector at this voltage.

I agree that the outdoor use of this particular epoxide resin is not entirely satisfactory, owing to the effect of ultra-violet light on the surface. Experience is being gained both on the 25 kV British Railways system and in South Africa on the 3 kV d.c. lines to see if its superior mechanical strength outweighs the disadvantage of regular cleaning.

The preliminary covering of metal parts embedded in the resin with a layer of p.v.c. is an unnecessary complication, and the choice of suitable fillers and an appropriate production control could avoid its use. The p.v.c. only rounds the edges of the copper, thus obviating stress area, and could trap air.

A modern technique for the manufacture of high-voltage bushings has been evolved where an electrolytic-bath model is first made and where various arrangements of screen can be tried to obtain the best field form. Very accurate forecasts for a bushing performance can be obtained from this technique, and very much better voltage distribution has been obtained as a result of this preliminary work.

Standard bushings for 34·5 kV service which both in the United States and Canada are common to switchgear and transformers have been manufactured where the following tests figures were obtained:

Momentary dry withstand (B.S. 223) ..	123 kV
Tests for under oil flashover	155 kV
Full-wave withstand (impulse voltage) ..	290 kV
Wet withstand (with 46 kV weather shed) ..	160 kV
Wet flashover (with 46 kV weather shed) ..	165 kV
Corona inception by detector.. ..	above 30 kV

The advantages of a moulded bushing with a porcelain weather shed are that there is no oil necessary and, therefore, no heavy top cap, and there is no metal flange, as the flange is incorporated in the moulding. A further advantage is that the porcelain is less expensive, as no great dimensional accuracy is required. This technique could be employed on bushings up to 132 kV, and a much better stress distribution could be obtained with control screens formed, or shaped, to comply with the field. This is a technique which cannot be applied to s.r.b.p. bushings.

Already, mouldings with stress control for applications other than switchgear have been manufactured for 132 kV service, and they are capable of withstanding over 900 kV peak impulse voltage.

I think that this development is one of the most important advances in the past 30 years, and it is likely to bring the bulk-oil circuit-breaker back into its own, as moulded bushings are less expensive than s.r.b.p. bushings.

Mr. J. K. Czernuszka: Since the paper was written, much progress has been made in the design of new apparatus and in the manufacture of resins by introducing new grades.

In Section 2.1 it is stated that 14 hours are required to complete the cure of Araldite at 120°C. The manufacturers give 12 hours at 120°C, but from my own experience I would suggest something more like 16 or even 20 hours.

I agree that the maximum mechanical properties of the material are obtained after curing to the times given by the manufacturers, but after a certain time, especially in service on full load, the mechanical strength of the material will drop by about 20–30%. Items which have been cured for short periods, then assembled in prototypes and tested, will give a false picture, because a few years later in service the component is likely to break under a short-circuit fault which has produced lower stresses than the testing condition. Therefore it is sound policy to ensure that the product is fully cured before it is assembled in the unit.

From Fig. 2, in spite of the fact that the phthalic anhydride absorbs moisture readily, how is it possible to have as much as 2% of water present in the mixture? The high temperature and the vacuum are bound to remove most of the moisture.

I agree that the power-factor/voltage tests are unsuitable and that the discharge detector should be used, but I am surprised that the authors talk about discharges in vacuum-cast components. These in essence consist, if properly processed, of almost homogeneous material. If the article is properly designed there should be no internal discharges, and the only discharges that are likely to occur are those caused by the stress on the surface on over-voltage.

It is now possible (see Section 4) to incorporate specially shaped electrodes in the epoxy-resin-insulated bushings in such a way that the stress is greatly relieved, and thus it is possible to produce bushings for higher voltages.

In Section 5 the authors condemn epoxy resin for outdoor use; in France, however, epoxy insulators have been in use for the last 3½ years without showing any signs of deterioration. Furthermore, these insulators were cast in moulds with a high surface quality, and they are not coated with grease or any other surface-finishing substance.

Mr. E. K. Long: My company has also been using epoxy-resin castings for some years now, often with great advantage; for example, a 3-phase T-off casting containing some 26 lb of mix reduced the dimensions of a ring-main unit by several inches.

In some other applications, however, Araldite has its shortcomings. When used for a bushing or spout in air as distinct from oil it may often give inferior results to porcelains on impulse

* MANLEY, T. R., ROTHWELL, K., and GRAY, W.; Paper No. 2835 S, February, 1959 (see 107 A, p. 213).

tests. An impulse level of about 90 kV can be reached by going up in small steps, but if flashover occurs at the next step, it will continue down to some very much lower figure, say 60 kV. This is due to a surface-charge phenomenon. Both time between impulses and the polarity of the previous impulse have considerable bearing on results, and in order to comply with the B.S. test series it is necessary to carry out a preliminary series, changing polarity before every shot, to establish a true level which can be guaranteed without resorting to polarity conditioning. As the authors say, the application of condenser-bushing techniques is difficult, and on tests which we have carried out no worth-while alleviation of this charge phenomenon was obtained. Do the authors know of any satisfactory solution to this problem, which is of some importance in certain tropical regions where the use of paper-based bushings is not always approved?

In contrast, we have found that current transformers, particularly where the two primary connections are adjacent, give tolerably good impulse results without resorting to special techniques.

Mr. S. Whittam: Referring to Fig. 4 and Section 8, the method does not differentiate between the contractions in the liquid and gelled states. Total shrinkage is unsatisfactory for comparing systems or curing temperatures. From Fig. 4, taking into account the viscosity changes, most of the shrinkage at the higher temperature occurs in the liquid phase and so the stresses in the cured casting would be less. This would be partially balanced by the increased stresses due to differential contraction on cooling.

Fig. 6 shows the stress reduction obtained using p.v.c. cushioning, although there appears to be a considerable amount remaining. P.V.C. is virtually incompressible, so that where it is completely within the mass its function is to even out the stresses, and particularly to round off the corners. A considerable part of this improvement might be obtained by rounding off the corners of the bar. Similarly a rubber-like material gives little protection during over-current tests on current transformers, a gas such as in the interstices of a foam being necessary.

Polarized-light examination should be useful, but assessment of the limit of stress acceptable is difficult; only extremely simple castings would be completely stress free. It cannot be used for complex castings where it is impossible to obtain sound castings without using fillers.

Pot-life problems are eased using polyesters for impregnation, but the greater contraction is likely to lead to internal discharge, owing to the increased probability of internal cracks and voids.

Were the discharge tests made on a detector or an Arman and Starr bridge? The meaning of 200 pC is considerably different with the two methods.

Have the authors any evidence of internal voids being short-circuited out after discharging for a period? Many discharge tests reported have been carried out in free air on the insulation surface and may be misleading.

Mr. C. H. Berry: Some relief from strain concentration is possible by shaping conductors to avoid sharp edges and by controlled cooling in an annealing process, which has been found to work very well with castings without inserts and to a limited extent with castings with inserts.

With regard to the use of p.v.c. taping of conductors for cushioning, can the authors explain how deformation and consequent void formation is avoided on short-circuit tests, as I would expect the p.v.c. to change its shape under such conditions? In my experience a cushioning material should contain a compressible air layer to be effective and must be short-circuited by a conducting layer on its surface to eliminate discharges. It is important that the air cushion is sealed from the resin.

In Section 3.4 the authors refer to duration tests at 50 c/s and state that the discharges are in excess of 200 pC and there is no evidence of deterioration so far. Could the authors state the voltage stress of the material being tested? Has the discharge magnitude remained constant during this period? My experience is that in some cases discharges decrease in magnitude with time and, unless a periodic check is made, a duration test may be misleading. Have the authors devised a method of assessing the degree of impregnation in a high-voltage winding, and are routine checks made on production to check this?

With regard to safe working stress the authors have adopted 40 volts/mil as a design parameter for epoxy resins. Presumably this is for filled resin. Have the authors similar information on the life of unfilled resin and polyester resin, which they use for impregnating high-voltage windings?

Finally, with regard to the use of cast resin for outdoor use a method adopted on the Continent consists of embedding the main body of the insulator in cast resin and fitting it with porcelain skirts to shield it from sunlight and direct rain. Do the authors consider this method satisfactory?

Messrs. T. R. Manley, K. Rothwell and **W. Gray** (*in reply*): *To Mr. J. R. Ferguson.*—There are situations where we have found it impossible satisfactorily to manufacture moulding without first covering the copper conductors with a layer of p.v.c.

To Mr. J. K. Czernuszka.—We agree that there may be some reduction in certain mechanical properties of Araldite B when working under full-load service conditions caused by a slight increase in thermo-plasticity. However, we cannot agree that this would be responsible for the failure of a casting under short-circuit conditions. One possible explanation is that the casting was initially in a highly stressed state and that fine cracks developed during temperature variations which resulted in final failure developing under short-circuit conditions.

With regard to Fig. 2, the mixing times are short and the rate of the reaction with water is rapid, resulting in the catalytic action shown.

Since the paper was written, considerable work has been done both in this country and on the Continent on the manufacture of high-voltage resin bushings with condenser layers, and the prospects are that this will have a considerable influence on future switchgear designs.

Our experience of both British and Continental insulators outdoors is that the surface rapidly becomes covered with track marks and would therefore not be suitable for use in this country. However, it is interesting to note that, if the insulator which has started to track is cleaned, the breakdown path does not progress further, but track marks appear at points remote from the original path.

To Mr. E. K. Long.—We agree that a surface-charge phenomenon causes difficulty during impulse tests on some cast-resin articles, but as yet no satisfactory solution has been found.

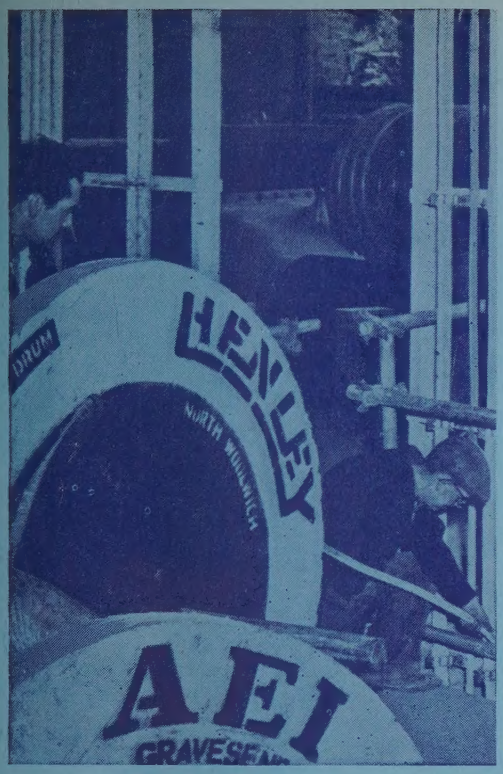
To Mr. S. Whittam.—The majority of the discharge results quoted in the paper were obtained using a discharge bridge developed from that described by Arman and Starr.*

To Mr. C. H. Berry.—Routine discharge tests are made on all voltage transformers above 11 kV using a discharge detector (direct method) and applying an induced primary voltage.

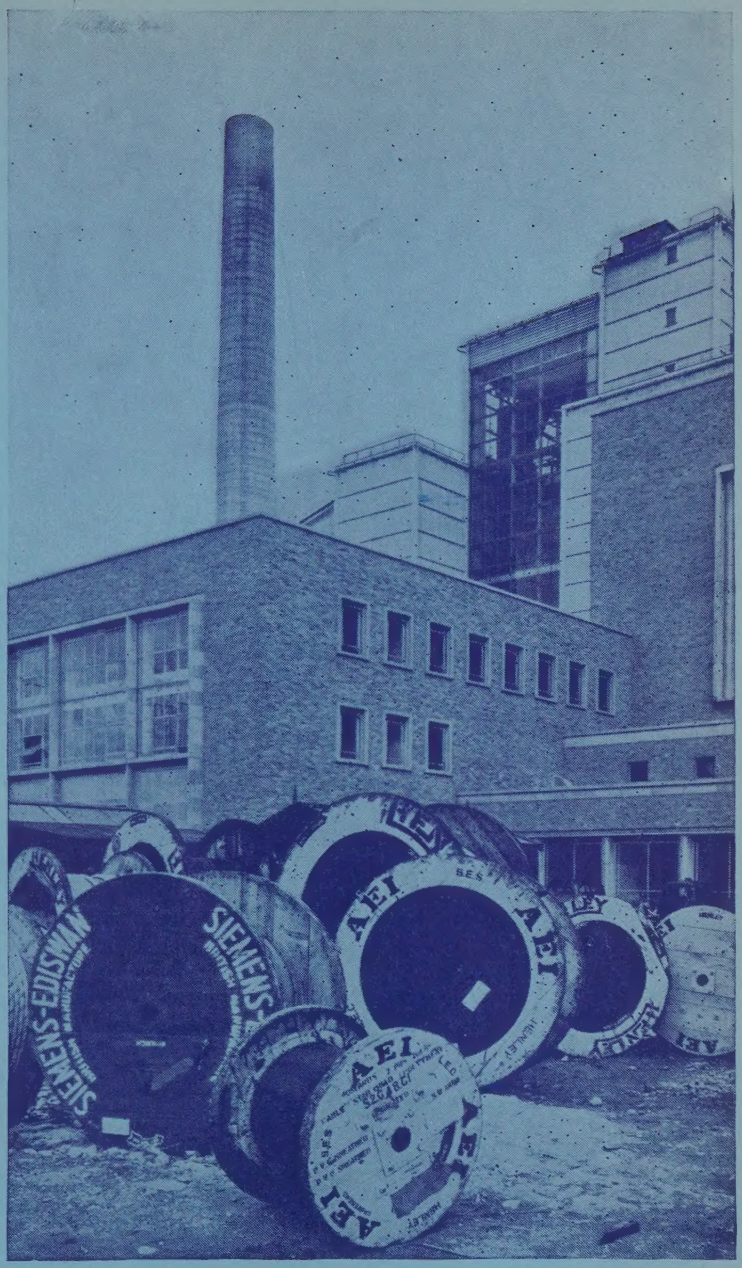
We have no information on the discharge life of paper impregnated with polyester resin, but the discharge life of paper impregnated with Araldite F is of the same order as s.r.b.p.

We have tried the method of fitting porcelain skirts to cast resin insulators, but there are difficulties in ensuring complete and consistent filling of the gap between porcelain and resin.

* ARMAN, A. N., and STARR, A. T.: 'The Measurement of Discharges in Dielectrics', *Journal I.E.E.*, July, 1936, 79, p. 67.







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Part A. POWER ENGINEERING, FEBRUARY 1961

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